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Ordovician calcified cyanobacteria and associated microfossils from the Tarim Basin, Northwest China: systematics and significance

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Calcified cyanobacteria and associated microfossils were examined in 8500 thin sections of Ordovician core samples from 64 wells in carbonate platforms of the Tarim Basin, Xinjiang Province, Northwest China. They include 32 species (including three uncertain species) belonging to 20 genera, most of which are from the Middle and Upper Ordovician. Two new genera and species, *Acuasiphonoria ordovica* gen. et sp. nov. and *Gomphosphon xinjiangensis* gen. et sp. nov., and two new species, *Proaulopora pachydermatica* sp. nov. and *Rothpletzella longita* sp. nov., are described. Calcified cyanobacteria include *Girvanella*, *Subtifloria*, *Razumovskia*, *Acuasiphonoria* gen. nov., *Hedstroemia*, *Cayeuxia*, *Bija*, *Apophoretella*, *Ortonella*, *Zonotrichites* and *Bevocastria*. Probable calcified cyanobacteria include *Proaulopora*, *Phacelophyton* and *Gomphosphon* gen. nov. Calcified Microproblematica include *Renalcis*, *Izhella*, *Epiphyton*, *Wetheredella*, *Rothpletzella* and *Garwoodia*. This assemblage is diverse in comparison with similar Ordovician fossils reported from other areas, and includes six genera and 14 species recorded from the Ordovician for the first time. Calcified cyanobacteria and their associated microfossils are more diverse in the Middle and Late Ordovician than was previously known.

Keywords: calcified cyanobacteria; calcified microfossils; Ordovician; Tarim Basin; taxonomy; diversity

Introduction

Cyanobacteria are a key component of marine primary productivity (Falkowski & Knoll 2007). Although they generally only calcify weakly or not at all in present-day oceans, marine calcified cyanobacteria and associated calcified microfossils are locally common at times during the Proterozoic, Palaeozoic and Mesozoic (Riding 1982, 1992; Pentecost & Riding 1986; Komar 1989; Arp *et al.* 2001). These secular variations in calcification may reflect long-term changes in seawater chemistry and in atmospheric carbon dioxide (Riding 1982, 1992; Thompson & Ferris 1990; Riding 1992; Kempe & Kazmierczak 1994; Riding & Liang 2005; Riding 2006). However, tracking the geological history of calcified cyanobacteria is hindered by the relative morphological simplicity of their fossils (Konhauser & Riding 2012). The lack of distinctive criteria makes it difficult to recognize confidently calcified cyanobacteria and creates instabilities in the taxonomy of these and superficially similar calcified microbes (Riding & Voronova 1982).

During the Ordovician, marine metazoans underwent significant diversification. Numerous calcareous-shelled brachiopods, crinoids, stromatoporoids, tabulate corals,

rugose corals, bryozoans, nautiloids and other organisms appeared (Webby *et al.* 2004; Rong *et al.* 2006; Servais *et al.* 2010). In contrast, there have been relatively few studies of Ordovician calcified cyanobacteria and algae (Nitecki *et al.* 2004), and the components of calcified cyanobacteria included in the ‘Ordovician Flora’ by Chuvashov & Riding (1984) were not well defined. Ordovician calcified cyanobacteria are known from Europe (Høeg 1932; Nicholson & Etheridge 1878), USA (Klement & Toomey 1967; Riding & Toomey 1972; Walker 1972; Toomey & Lemone 1977), Canada (Copper 1976; Guilbault & Mamet 1976; Mamet & Shalaby, 1995; Mamet *et al.* 1992; Pratt & Haidl 2008), Argentina (Beresi & Heredia 2003) and China (South China: Bian & Zhou 1990, Adachi *et al.* 2009; 2011; 2013; Kwon *et al.* 2012; North China: Ye *et al.* 1995; Lee *et al.* 2014; Tarim Basin, Riding & Fan 2001; Wang *et al.* 2009, 2011; Liu *et al.* 2011; Zhang *et al.* 2014; Rong *et al.* 2014). However, the total number of genera of calcified cyanobacteria reported from any one of these locations does not exceed eight. The question this poses is the extent to which these results reflect marine calcified cyanobacterial diversity during the Ordovician.

We have carried out an extensive study of calcified cyanobacterial fossils in 8500 thin sections of drill core

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samples from 64 wells in the Tazhong, Tabei, Bachu and Tadong areas of the Tarim Basin, which together span most of the Ordovician. The initial results indicated unexpectedly high levels in both abundance and diversity of calcified cyanobacteria, especially during the Late Ordovician (Liu *et al.* 2011). Here, we describe calcified cyanobacteria, probable cyanobacteria, and associated microfossils from 8500 thin sections of drill core samples from 64 wells spanning almost the entire Ordovician. These fossils include at least 32 species (with four new species erected) belonging to 20 genera (two new genera erected). This is the most diverse flora of calcified cyanobacteria so far known from the Ordovician.

Geological setting

Tarim Basin

The Tarim Basin is located in the Xinjiang Province of Northwest China, and is bordered by four mountain ranges, Kunlun on the south and south-west, Altun on the south-east, Tianshan on the north-west, and the Kuluketak on the north-east (Fig. 1A, B). The Tarim Basin is more than 500 km wide and 1000 km long, and is largely floored by recent desert deposits, but outcrops of Precambrian, Palaeozoic and Mesozoic rocks occur around its margins.

The Tarim Block, together with the North and South China blocks, is one of the three major continental blocks in China. It consists of pre-Neoproterozoic basement overlain by a late Neoproterozoic to Early Permian sequence of marine deposits followed by a Late Permian–Quaternary continental sequence (Jia *et al.* 1997). It experienced several stages of tectonic development that show both similarities and differences with those of North and South China (Zhang *et al.* 2012), and has been divided into a number of subunits (Fig. 1C; Jia *et al.* 1995).

Ordovician carbonate platform stratigraphy

Extensive Ordovician carbonate platforms developed on the Tabei, Bachu, Tazhong and West Tadong uplifts. The platform was united during the Early Ordovician but became divided into the Tabei platform and the Bachu-Tazhong platform in the Middle Ordovician, as revealed by outcrop and subsurface well and seismic data (Feng *et al.* 2007; Zhao *et al.* 2009). These platforms are 2000–6000 m thick, and have been penetrated by the 64 wells used in our research (Fig. 1C).

Stratigraphical studies (Zhou & Chen 1990; Ni *et al.* 2001; Gu *et al.* 2005; Zhu *et al.* 2006; Cai *et al.* 2007; Cai & Li 2008; Yang *et al.* 2009) have divided the Ordovician deposits of these areas into six formations, from bottom to top: the Penglaiba (O_{1p}) (~1000 m), Yingshan (O_{1-2y}) (~500 m), Yijianfang (O_{2y}) (~100–200 m), Tumuxiuk (O_{3t}) (~20–50 m), Lianglitag (O_{3l}) (~200–300 m thick in Bachu, ~600–800 m in Tazhong, and ~100–200 m in Tabei) and Sangtam (O_{3s}) (~500 m) formations,

spanning most of the Ordovician (Fig. 2). The Yijianfang and Tumuxiuk formations are absent in most of the south-western area (Tazhong and Bachu) due to uplift during the Middle and Late Ordovician (Fig. 2; Zhou & Chen 1990; Xiong *et al.* 2006; Zhao *et al.* 2006; Wang *et al.* 2007; Cai *et al.*, 2008; Li *et al.* 2009; Zhao *et al.* 2010).

Previously, Riding & Fan (2001) when describing Ordovician calcified cyanobacteria and algae from Tarim Basin Ordovician successions, regarded boreholes YM2, YM1, and LN46 as mainly Early and Middle Ordovician, based on the age data then available. However, subsequent research has shown that most of the successions in these boreholes are Middle and Late Ordovician, as inferred by Nitecki *et al.* (2004). Current datings now suggest the following ages. In boreholes YM1 and YM2, samples YM1-26 to YM1-23 and YM2-56 to YM2-42 are from the Yijianfang Formation and are Middle Ordovician in age, rather than Early Ordovician; and samples YM1-22 to YM1-1 and YM2-82 to YM2-78 are from the Lianglitag Formation and are Late Ordovician in age, rather than Middle Ordovician. In borehole LN46, samples LN46-128 to LN46-123 are from the Yijianfang Formation and are Middle Ordovician in age, but previously were regarded as Early Ordovician; samples LN46-122 to LN46-95 are from the Lianglitag Formation and are of Late Ordovician age, but previously were regarded as Middle Ordovician, and samples LN46-94 to LN46-2 are from the Sangtam Formation and are of Late Ordovician age, although some of them were previously regarded as Middle Ordovician.

Lithology and sedimentary facies

The Ordovician formations summarized above are predominantly carbonates (Fig. 2). The Penglaiba Formation is mainly laminated dolomite with limestone interbeds, and is considered to be a restricted platform deposit (He *et al.* 2007; Cai & Li 2008; Zhao *et al.* 2009). The Yingshan Formation consists of bedded lime mudstone, wackestone and grainstone interpreted as open platform and platform margin facies (He *et al.* 2007; Cai & Li 2008). The Yijianfang Formation is mainly grainstone and *Calathium* reef limestone, regarded as platform margin deposits (Zhou & Chen 1990; Gu *et al.* 2005; Zhu *et al.* 2006; Li *et al.* 2007; Cai & Li 2008; Li *et al.* 2009; Wang *et al.* 2012). The Tumuxiuk Formation is mainly fine-grained condensed red argillaceous limestones, interpreted as a relatively deep-water pelagic deposit (Li *et al.* 2009). The Lianglitag Formation at the southern and northern margins of the Bachu-Tazhong platform is a reef margin deposit composed of corals, stromatoporoids and calcareous algae (Gu *et al.* 2005; Cai *et al.* 2008; Li *et al.* 2009; Yang *et al.* 2010; Wang *et al.* 2012). In the inner part of the Bachu-Tazhong platform this formation is mainly wackestone and lime mudstone, regarded as tidal flat and lagoon facies (Yang *et al.* 2010; Gao *et al.* 2014), whereas in Tabei the formation is mainly packstone and

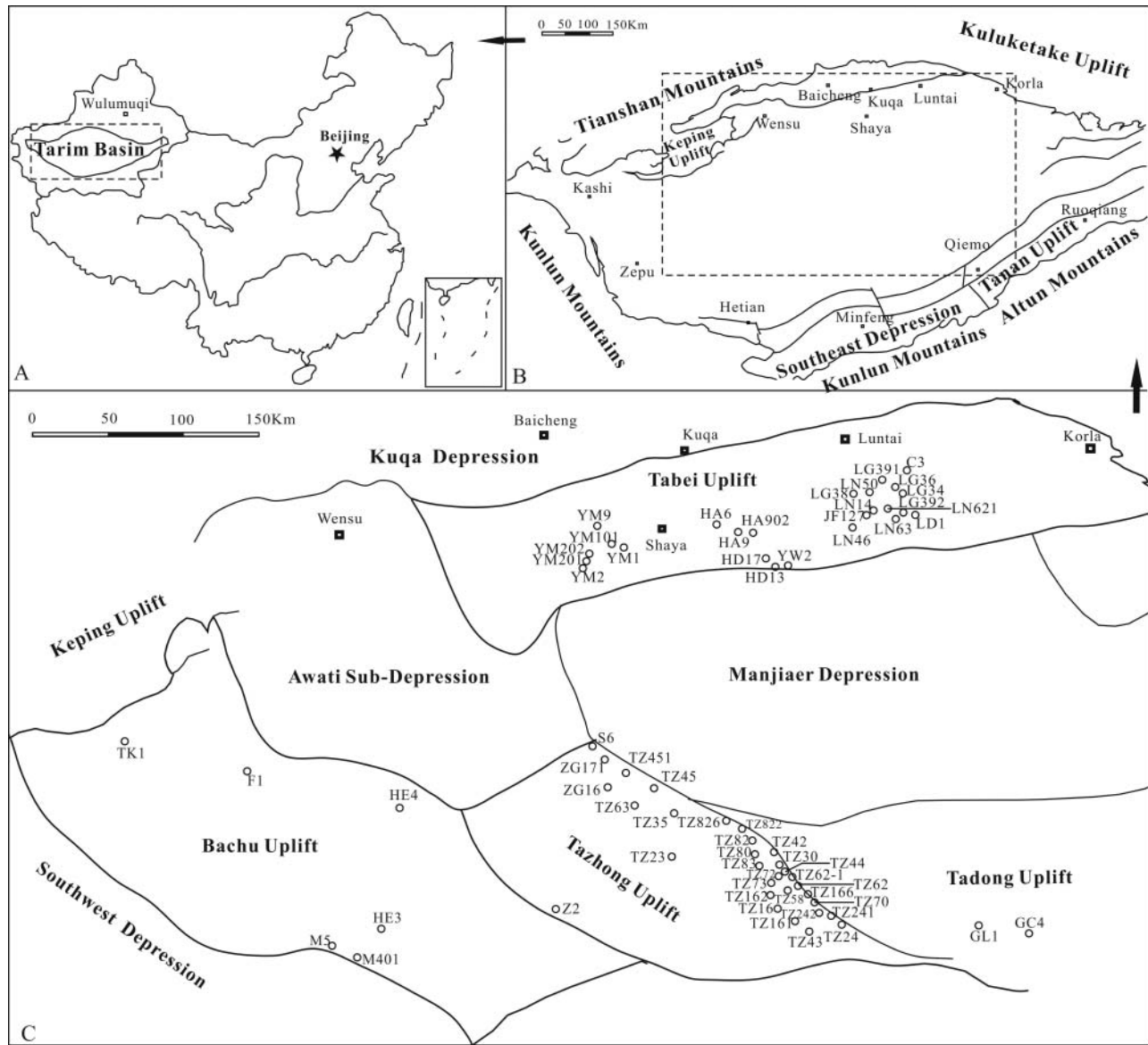


Figure 1. Regional setting of the Tarim Basin showing tectonic and depositional areas and locations of the wells mentioned in this study.

green algal reef limestone, interpreted as open platform deposits. The Late Ordovician Sangtamu Formation is mainly a mixed terrigenous clastic and carbonate deposit of greenish sandy argillaceous mudstone interbedded with argillaceous limestone (Feng *et al.* 2007; Zhang *et al.* 2007; Cai & Li 2008; Yang *et al.* 2011).

Material and methods

More than 8500 large (5 × 7 cm) thin sections of drill core samples from 64 wells (Fig. 1) were prepared. These samples cover the entire Ordovician carbonate succession in the area studied (Online Supplementary Material Table 1).

The thin sections were investigated using transmitted light microscopy and microphotography, revealing numerous calcified cyanobacteria, probable cyanobacteria and associated calcified microfossils. Many examples of these fossils in the thin sections were measured, and more than 10,000 microphotographs were taken.

Based on these thin sections, we identified 32 species amongst 20 genera, including two new genera and four new species, as illustrated in Figure 3. The material is conserved in the collection of the Institute of Geology and Geophysics, Chinese Academy of Sciences (C-IGG-CAS), Beijing, China and the collection of the Exploration and Development Institute, PetroChina Tarim Oilfield Company (C-PCTOC), Korla, Northwest

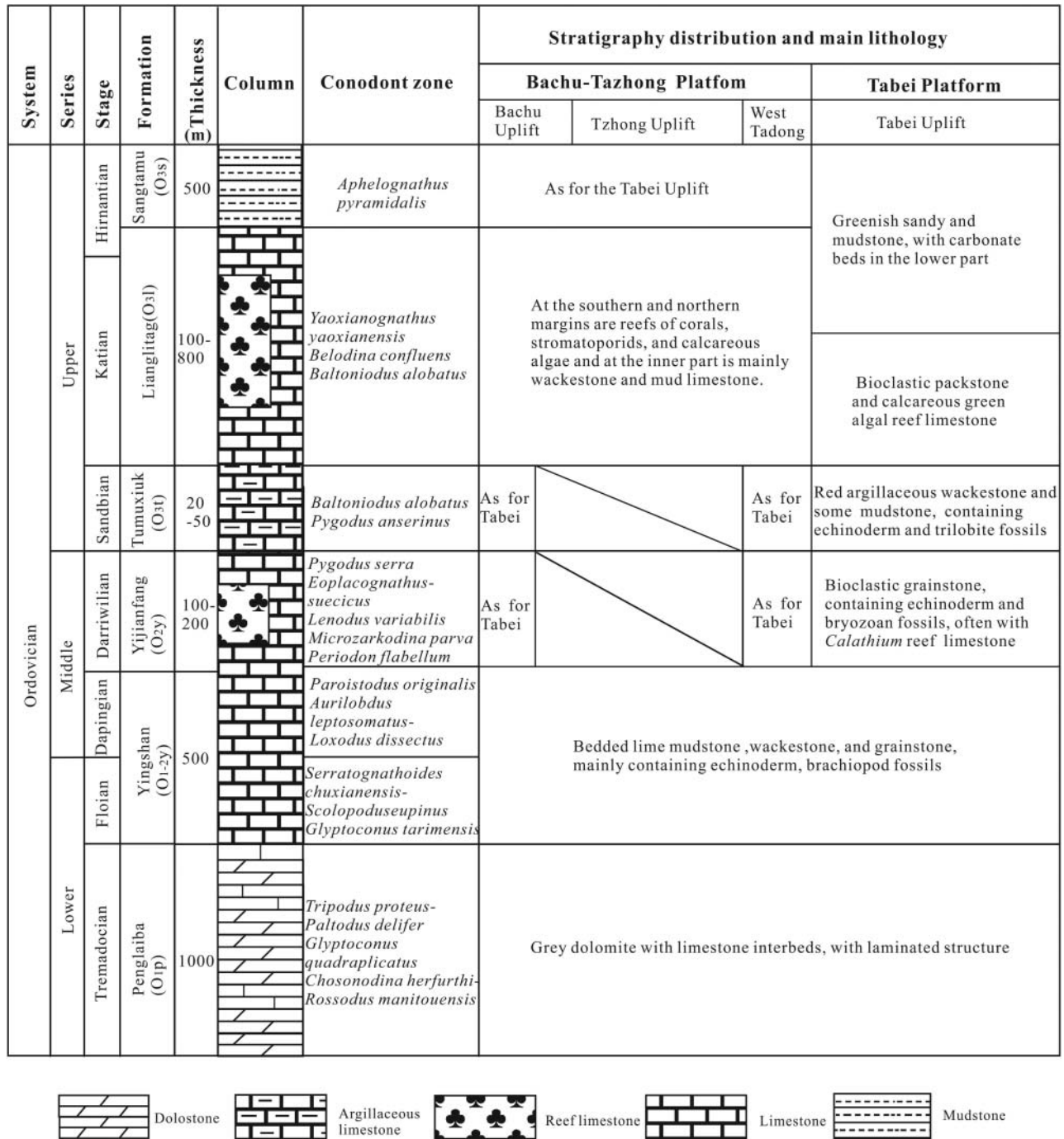


Figure 2. Stratigraphy and lithology of the Ordovician succession studied in the Tarim Basin (based on Zhou & Chen 1990; Ni *et al.* 2001; Cai *et al.* 2007; Cai & Li 2008; Li *et al.* 2009; Yang *et al.* 2009; Zhao *et al.* 2010).

China. Both collections are public and have a policy of providing access for bona fide researchers. The holotypes of *Gomphosiphon xinjiang* gen. et sp. nov. and *Rothpletzella longia* sp. nov. are housed in the C-PCTOC, and those of *Proaulopora pachydermatica* sp. nov. and *Acuasiphonoria ordovica* gen. et sp. nov. are in the C-IGGCAS.

Nineteen genera (with exception of *Epiphyton*) are present in the Lianglitag Formation, seven genera (*Girvanella*, *Rothpletzella*, *Wetheredella*, *Epiphyton*, *Renalcis*, *Proaulopora*, *Subtifloria*) in the Yijianfang Formation, three genera (*Girvanella*, *Wetheredella*, *Rothpletzella*) in carbonate beds of the Sangtamu Formation, and two genera (*Girvanella*, *Proaulopora*) in the Yingshan Formation (Fig. 3). None of

Taxonomy	Number	Genus	Species	Occurrence	Sketch	Probable modern analogues
Cyanobacteria	1	<i>Girvanella</i>	<i>G. kasakiensis</i> <i>G. problematica</i> <i>G. wetheredii</i> <i>G. staminea</i> <i>?G. sp.</i>	O1-2y, O2y, O3l, O3s		<i>Plectonema</i>
	2	<i>Subtifloria</i>	<i>S. delicata</i>	O2y, O3l		<i>Microcoleus</i>
	3	<i>Razumovskia</i>	<i>R. sp.</i>	O3l		<i>Phormidium</i>
	4	<i>Acuasiphonoria</i> gen. nov.	<i>Acuasiphonoria</i> <i>ordovica</i> gen. et sp. nov.	O3l		Oscillatoriacean cyanobacterium
	5	<i>Hedstroemia</i>	<i>H. halimedoidea</i> <i>H. bifilosa</i>	O3l		<i>Rivularia</i>
	6	<i>Cayeuxia</i>	<i>C. moldavica</i> <i>C. pieae</i>	O3l		
	7	<i>Bija</i>	<i>B. sibirica</i>	O3l		
	8	<i>Apophoretella</i>	<i>A. dobunorum</i>	O3l		
	9	<i>Ortonella</i>	<i>O. furcata</i> <i>O. tenuissima</i> <i>O. kershopenensis</i>	O3l		
	10	<i>Zonotrichites</i>	<i>Z. lissaviensis</i>	O3l		
	11	<i>Bevoastria</i>	<i>B. conglobata</i>	O3l		uncertian
? Cyanobacteria	12	<i>Proaulopora</i>	<i>P. rarissima</i> <i>P. pachydermatica</i> sp. nov.	O1-2y, O2y, O3l		<i>Dichothrix</i> (12) <i>Calothrix</i> (13,14)
	13	<i>Phacelophyton</i>	<i>P. yushanensis</i>	O3l		
	14	<i>Gomphosphon</i> gen. nov.	<i>G. xinjiangensis</i> gen. et sp. nov.	O3l		
Microproblematica	15	<i>Renalcis</i>	<i>R. seriata</i> <i>R. granosus</i>	O2y, O3l		uncertian
	16	<i>Izhella</i>	<i>I. nubiformis</i>	O3l		
	17	<i>Epiphyton</i>	<i>E. sp.</i>	O2y		
	18	<i>Wetheredella</i>	<i>W. silurica</i>	O2y, O3l, O3s		
	19	<i>Rothpletzella</i>	<i>R. gotlandica</i> <i>R. longita</i> sp. nov.	O2y, O3l, O3s		
	20	<i>Garwoodia</i>	<i>G. gregaria</i> <i>G. americana</i>	O3l		

Figure 3. Taxa of calcified cyanobacteria, probable cyanobacteria and associated calcified microproblematic fossils from the Tarim Basin Ordovician, and selected possible present-day analogues. The genera and species in bold have not previously been recorded elsewhere from the Ordovician.

these fossils have been found in the Penglaiba and Tumuxiuk formations. It is evident that their stratigraphical distributions in the Tarim Ordovician successions mainly depend on the sedimentary facies of each formation, but we infer that they also reflect the macroevolutionary development of these taxa during the Ordovician.

We describe and compare these taxa to those of previous studies (e.g. Bornemann 1886; Pia 1927; Maslov 1956; Elliott 1964, 1975; Korde 1973; Hofmann 1975; Luchinina 1975; Riding 1977a, b; Riding & Voronova 1982; Dragastan 1985, 1993; Chuvashov *et al.* 1987; Riding 1991a; Kaźmierczak & Kempe 1992, 2004; Laval *et al.* 2000; Riding & Fan 2001; Woo & Chough 2010; Jarochowska & Munnecke 2014), as well as with modern analogues (Fig. 3). 6 genera and 14 species in our Tarim samples which do not appear to have been recognized elsewhere in the Ordovician are indicated in bold in Figure 3.

Systematic palaeontology

Cyanobacteria Stanier, 1974

Genus *Girvanella* Nicholson & Etheridge, 1878

1973 *Nicholsonia* Korde: 212, pl. 43, fig. 3, pl. 44, fig. 1, pl. 45, fig. 1.

Type species. *Girvanella problematica* Nicholson & Etheridge, 1878; Upper Ordovician, Scotland.

Diagnosis. Calcareous tubular filaments; uniform external diameter; long, sinuous to irregularly tangled; wall thin, micritic (Fig. 3).

Comparison. *Girvanella* has similarities with a variety of taxa that share its small size and simple tubiform morphology but which typically have more orderly arrangement, such as coiled (*Obruchevella* Reitlinger, 1948), prostrate curving to erect (*Razumovskia* Vologdin, 1939), and as more-or-less parallel bundles (*Subtifloria* Maslov, 1956; *Batinevia* Korde, 1966; *Cladogirvanella* Ott, 1966). Danielli's (1981, p. 96) suggestion that *Batinevia* is a synonym of *Girvanella* is mistaken, but *Nicholsonia* is a synonym. Luchinina (1975) created Girvanellaceae to contain *Girvanella* and *Obruchevella*, and Batineviaceae for *Batinevia*. Subsequently, Luchinina (in Chuvashov *et al.* 1987) also placed *Razumovskia* in Girvanellaceae. Riding (1991a) placed *Girvanella*, *Obruchevella* and *Subtifloria* in the *Girvanella* Group. *Girvanella* is similar in overall morphology to the uncalcified (usually silicified or organic-walled compressions in shales) microfossil *Siphonophycus* Schopf, 1968, which is widespread in Proterozoic microbial mats (see Schopf 2012).

Affinity. Bornemann (1886) regarded *Girvanella* as a cyanobacterium, as did Pollock (1918) who interpreted it

as a calcified sheath. Frémy & Dangeard (1935) compared *Girvanella* with *Symploca*, and Riding (1977a) compared it with the present-day calcified sheaths of *Plectonema* (Fig. 3). We therefore tentatively regard *Girvanella* as calcified sheaths of oscillatoriaceans.

Remarks. Wood (1957, p. 24, fig. 1) showed that detailed measurements of *Girvanella* from the type area did not reveal clear subgroups. Nonetheless, researchers have created numerous species of *Girvanella* mainly based on tube diameter; Fournie (1967, table 2) listed about 20 species, many of which appear to have overlapping sizes. In an attempt to improve this system in Devonian and Carboniferous *Girvanella*, Mamet & Roux (1975) proposed recognition of just four species – *G. kasakiensis*, *G. problematica*, *G. wetheredii* and *G. staminea* – according to their internal diameter and wall thickness. Danielli (1981, p. 98) pointed out that this approach seems contrary to Wood's (1957) findings, and that dimensions of *Girvanella* from the type area “are distributed over most of the graph and do not fall into clusters”. Nonetheless, here we have employed Mamet & Roux's (1975) approach, and find that our Tarim specimens on the whole tend to conform to one or other of the following four species, placed in order of decreasing tube size.

Girvanella kasakiensis Maslov, 1949 emend.
Mamet & Roux, 1975
(Fig. 4A)

1949 *Girvanella ducii* var. *kasakiensis* Maslov: 6.

1965 *Girvanella* aff. *ducii* Chuvashov: 74, pl. 17, fig. 3.

1967 *Girvanella ducii* Wethered; Wray: 34, pl. 7, fig. 5.

1975 *Girvanella kasakiensis* Maslov; Mamet & Roux: 142, pl. 4, fig. 10; pl. 5, figs 1, 2, 9, 10.

2011 *Girvanella kasakiensis* Maslov; Liu *et al.*: 495, pl. 1, fig. 3.

Material. Locally present in the Lianglitag Formation (O₃l) of wells LG38, LN63, TZ822, TZ24, TZ73, TZ42 and LN14. These specimens mainly occur in reef limestones and oncolites.

Description. Filaments long, loosely tangled, prostrate; external diameter 26–28 µm; wall thickness 4–6 µm.

Girvanella problematica Nicholson & Etheridge,
1878 emend. Wood, 1957
(= *Girvanella ducii* Wethered, 1890 auct.)
(Fig. 4B)

1878 *Girvanella problematica* Nicholson & Etheridge: 23, pl. 9, fig. 24.

1890 *Girvanella ducii* Wethered: 280, pl. 11, fig. 2a–c.

1932 *Girvanella problematica* Nicholson & Etheridge; Høeg: 64, pl. 1, figs 4–6.

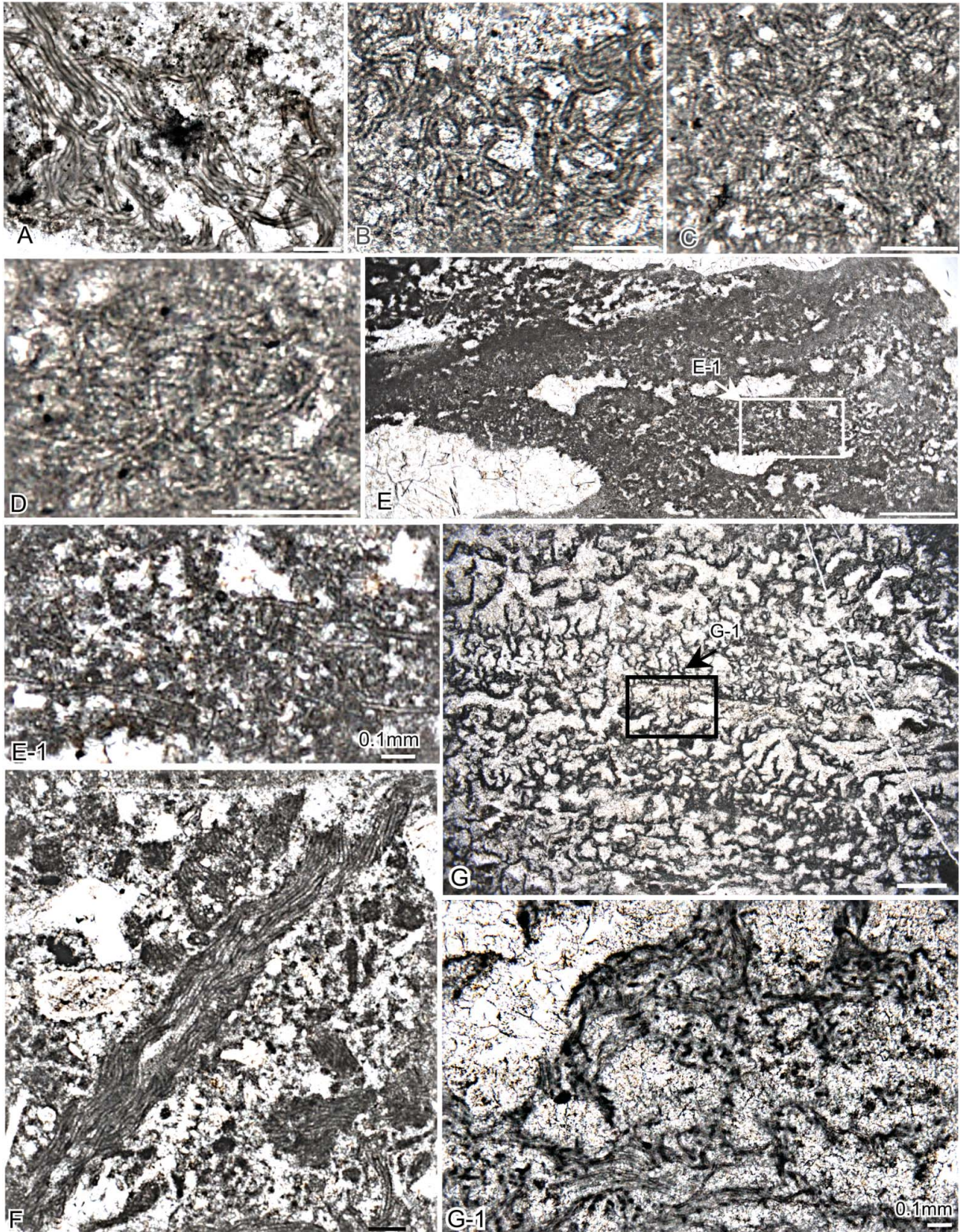


Figure 4. **A**, *Girvanella kasakiensis*, well LG38, sample no. 6-26-19, C-IGGCAS, O₃l, oblique longitudinal sections. **B**, *Girvanella problematica*, 4716.64 m depth, well TZ62, C-PCTOC, O₃l, oblique longitudinal section. **C**, *Girvanella wetheredii*, 5821.42 m depth, well TZ63, C-PCTOC, O₃s, oblique longitudinal section. **D**, *Girvanella staminea*, 4710.66 m depth, well TZ62, C-PCTOC, O₃l, oblique longitudinal section. **E**, **E-1**, ?*Girvanella* sp., well TK1, sample no. 26-15-8, C-IGGCAS, O₂y; **E-1**, enlargement of part of E. **F**, *Subtiffloria delicata*, well TK1, sample no. 10-24-24, C-IGGCAS, O₂y, longitudinal section. **G**, **G-1**, *Razumovskia* sp., well TZ42, sample no. 2-49-2, C-IGGCAS, O₃l; **G**, overall morphology; **G-1**, enlargement of part of G. All scale bars = 1 mm, except where indicated.

- 1981 *Girvanella problematica* Nicholson & Etheridge; Bourque *et al.*: 95, pl. 1, figs 2–4.
 2001 *Girvanella problematica* Nicholson & Etheridge; Riding & Fan: 789, text-figure 3B, C.
 2011 *Girvanella problematica* Nicholson & Etheridge; Liu *et al.*: 495, pl. I, fig. 4.

Material. Present in skeletal-peloid grainstones and packstones of the Yingshan Formation (O_{1-2y}) of well LN63, in skeletal grainstones of the Yijianfang Formation (O_{2y}) of wells TK1, HA902, HA9, HD17, YM1, YM2, YM201, YM202 and GC4, and in the oncolites and reef limestones of the Lianglitag Formation of wells TZ30, TZ44, TZ58, TZ62, TZ63, TZ70, TZ72, TZ73, TZ82, TZ83, Z161, TZ162, TZ241, TZ451, TZ822, TZ826, M5, M401, LN14, LN50, LN621, LN63, LG391, LG36 and JF127.

Description. Filaments long, tangled in mesh-like masses; external diameter 15–17 µm; wall thickness 2–4 µm.

Girvanella wetheredii Chapman, 1908
 (= *Girvanella incrustans* Wethered, 1890, non Bornemann, 1886)
 (Fig. 4C)

- 1974 *Girvanella wetheredii* Chapman; Mamet & Roux: 141, pl. 1, figs 9–12, pl. 161, pl. 2, figs 1–5.
 1995 *Girvanella wetheredii* Chapman; Mamet & Shalaby: 233, pl. 1, fig. 3.
 2011 *Girvanella wetheredii* Chapman; Liu *et al.*: 495, pl. 1, fig. 1.

Material. These specimens mainly occur in association with *Girvanella problematica*.

Description. Filaments irregularly tangled in mesh-like masses; external diameter 12 µm; wall thickness 2 µm.

Girvanella staminea Garwood, 1931
 (Fig. 4D)

- 1975 *Girvanella staminea* Garwood; Mamet & Roux: 140, pl. 1, figs 1–8.
 1995 *Girvanella wetheredii* Garwood; Mamet & Shalaby: 233, pl. 1, fig. 3.
 2011 *Girvanella staminea* Garwood; Liu *et al.*: 495, pl. 2, fig. 2.

Material. Locally present in oncolites of the Lianglitag Formation (O_{3l}) of wells TZ62 and TZ822.

Description. Filaments irregularly tangled into masses; external diameter 7 µm; wall very thin, difficult to measure.

?*Girvanella* sp.
 (Fig. 4E, E-1)

Material. Locally present in the Yijianfang Formation (O_{2y}) of well TK1 and the Lianglitag Formation (O_{3l}) of well TZ161. The specimens occur in fenestral micritic and peloidal limestones.

Description. Filaments long and randomly interlaced to form more or less dense mats; not tangled into masses; filament diameter *c.* 18 µm; wall thickness 3–4 µm.

Remarks. Resembles the poorly defined calcified tubes in Neoproterozoic lagoonal environments reported by Knoll *et al.* (1993, fig. 8), which is considered as *Girvanella* (Pratt 2001; Riding 2006), and morphologically resembles the silicified fossils *Siphonophycus solidum* and *Siphonophycus kestron* (see Butterfield *et al.* 1994) which are locally widespread in microbial mats in Proterozoic cherts (Schopf 2012), and are widely considered to be oscillatoriacean sheaths (Sergeev & Schopf 2010).

Genus *Subtifloria* Maslov, 1956

1959 *Botominella* Reitlinger: 25, pl. 10, figs 1–7.

Type species. *Subtifloria delicata* Maslov, 1956; Lower Cambrian; Siberian Platform, Russia.

Description. Calcified tubular filaments of uniform diameter, subparallel, often slightly sinuous, aggregated into bundles; filaments typically closely spaced, sometimes interlaced; wall thin, micritic (Fig. 3).

Comparison. *Subtifloria* is similar to some *Girvanella* in tube size, but differs in its overall cable-like, bundled arrangement of aligned filaments. Luchinina (1975) considered *Botominella* to be a junior synonym of *Subtifloria*. *Subtifloria latissima* from the Lower Carboniferous of the Kuzbass (Bogush *et al.* 1990, pl. 3, fig. 1) resembles *Girvanella*, as do some Silurian *Girvanella* (*G. fragile*, *G. proluxa*) from the Welsh Borderlands (Johnson 1966a, pls 6, 7). Some *Girvanella* reported from the Middle Ordovician of the Tarim Basin (Rong *et al.* 2014, fig. 5a, b) and from the Upper Ordovician of the Tarim Basin (Wang *et al.* 2009) are *Subtifloria*.

Affinity. Luchinina (in Chuvashov *et al.* 1987) compared *Subtifloria* with present-day *Microcoleus*, in which the filaments can be arranged in parallel bundles (Fig. 3). As with *Girvanella*, we regard *Subtifloria* as a sheath-calcified filamentous cyanobacterium (Feng *et al.* 2010).

Subtifloria delicata Maslov, 1956
 (Fig. 4F)

1956 *Subtifloria delicata* Maslov: 85, text-fig. 24, pl. 27, fig. 4.

- 1992 ?*Botominella* Reitlinger; Racki: fig. 3f.
 2001 ?*Subtifloria* sp. Riding & Fan: 790, text-fig. 3, fig. D.
 2009 *Girvanella* Nicholson & Etheridge; Wang *et al.*:
 fig. 2a.
 2011 *Subtifloria* sp. Liu *et al.*: 496, pl. 1, fig. 5.
 2014 *Girvanella* Nicholson & Etheridge; Rong *et al.*:
 fig. 5a, b.

Material. Present in the Yijianfang Formation (O_{2y}) of wells TK1, HA902, YM1, YM202, YM201, HD17 and YM2, and rarely present in the Lianglitag Formation (O_{3l}) of well TZ161. The specimens often occur in intraclastic and bioclastic grainstones.

Description. Filaments up to 12 mm long; external diameter ~27 µm, wall thickness ~5 µm.

Genus *Razumovskia* Vologdin 1939

- 1990 *Trichophyton* Bian & Zhou: 6 pl. 4, fig. 8 [Upper Ordovician, South China].

Type species. *Razumovskia uralica* Vologdin, 1937; Lower Cambrian; Siberian Platform, Russia.

Diagnosis. Calcareous tubular filaments, delicate, long and curved, wall thin and micritic. Filament arrangement complex, with loosely associated tubes curving vertically upwards from a prostrate felted mass (Fig. 3).

Comparison. *Razumovskia* differs from *Girvanella* in its distinctive overall arrangement. The Ordovician genus *Trichophyton* erected by Bian & Zhou (1990) is considered as *Razumovskia*. The genus *Trichophyton* is also reported from the Ordovician of the Ordos Basin of North China (Ye *et al.* 1995).

Affinity. Luchinina (1975) regarded *Razumovskia* as a calcified cyanobacterium. The pattern of its filament arrangement can be compared with some present-day *Phormidium* (Fig. 3).

Remarks. There are numerous species of *Razumovskia*, many described by Vologdin (1939), Korde (1973) and Drosdova (1980) from the Lower Cambrian of the Siberian Platform and Mongolia; most are based on subtle details of the microstructure or slight differences in filament diameter, and are difficult to distinguish with confidence.

Razumovskia sp. (Fig. 4G, G-1)

Material. Locally present in the Lianglitag Formation (O_{3l}) of wells TZ42 and TZ451. The specimens occur both in reef limestones and oncolites.

Description. Layers consisting of mainly horizontal filaments alternating with layers of mainly vertical filaments; filaments long, flexuous; external diameter ~8 µm, wall thickness 1–2 µm.

Genus *Acuasiphonoria* gen. nov.

Type species. *Acuasiphonoria ordovica* gen. et sp. nov.; Upper Ordovician, Katian, Lianglitag Formation; Tarim Basin, Xinjiang Province, Northwest China.

Species composition. Monospecific.

Etymology. *Acua* meaning acute; *siphon* meaning tubules.

Diagnosis. Gently curved long calcified tubes, ending in a sharp point; possibly branched at an acute angle; tube wall micritic (Fig. 3).

Comparison. *Acuasiphonoria* is distinguished from *Girvanella* by its long straight, or only slightly curved, filaments that appear to tapering, resembling needles.

Affinity. We regard *Acuasiphonoria* as an oscillatoriacean sheath, as for *Girvanella* (Fig. 3).

Acuasiphonoria ordovica sp. nov. (Fig. 5A–C)

Etymology. After its discovery in Ordovician strata.

Material. Holotype: thin section 4-53-49 from well TZ42, housed in the C-IGGCAS; Upper Ordovician, Katian, Lianglitag Formation; Tarim Basin, Xinjiang Province, Northwest China.

Locally present in the Lianglitag Formation (O_{3l}) of wells TZ24, TZ42, LN63 and TZ822. The specimens often occur in reef limestone.

Diagnosis. As for the genus.

Description. Long straight separated cylindrical filaments, slightly curved, locally at right angles, extending straight for up to 1 mm or more, external diameter ~14–24 µm, wall thickness up to 1 µm.

Genus *Hedstroemia* Rothpletz, 1913

Type species. *Hedstroemia halimedoidea* Rothpletz, 1913; Silurian, Wenlock; Gotland, Sweden.

Diagnosis. Calcareous microfossil composed of more or less radially arranged, closely packed tubes, dichotomously branched at a low angle, that expand distally (Fig. 3).

Comparison. Its organization of small juxtaposed radial filaments links *Hedstroemia* to a wide variety of common Palaeozoic and Mesozoic fossils, including *Garwoodia* (Nicholson 1888; Wood 1941: Carboniferous), *Ortonella* (Garwood 1914: Carboniferous), *Bija* (Vologdin 1932: Cambrian), *Cayeuxia* (Frollo 1938: Jurassic), *Botomaella* (Korde 1958: Cambrian), *Zonotrichites* (Bornemann 1887: Triassic) and *Apophoretella* (Elliott 1975: Jurassic). Some or all of these have been variously combined in Garwoodiaceae (Shuysky 1973; Chuvashov *et al.* 1987) or the *Hedstroemia* Group (Riding 1991a).

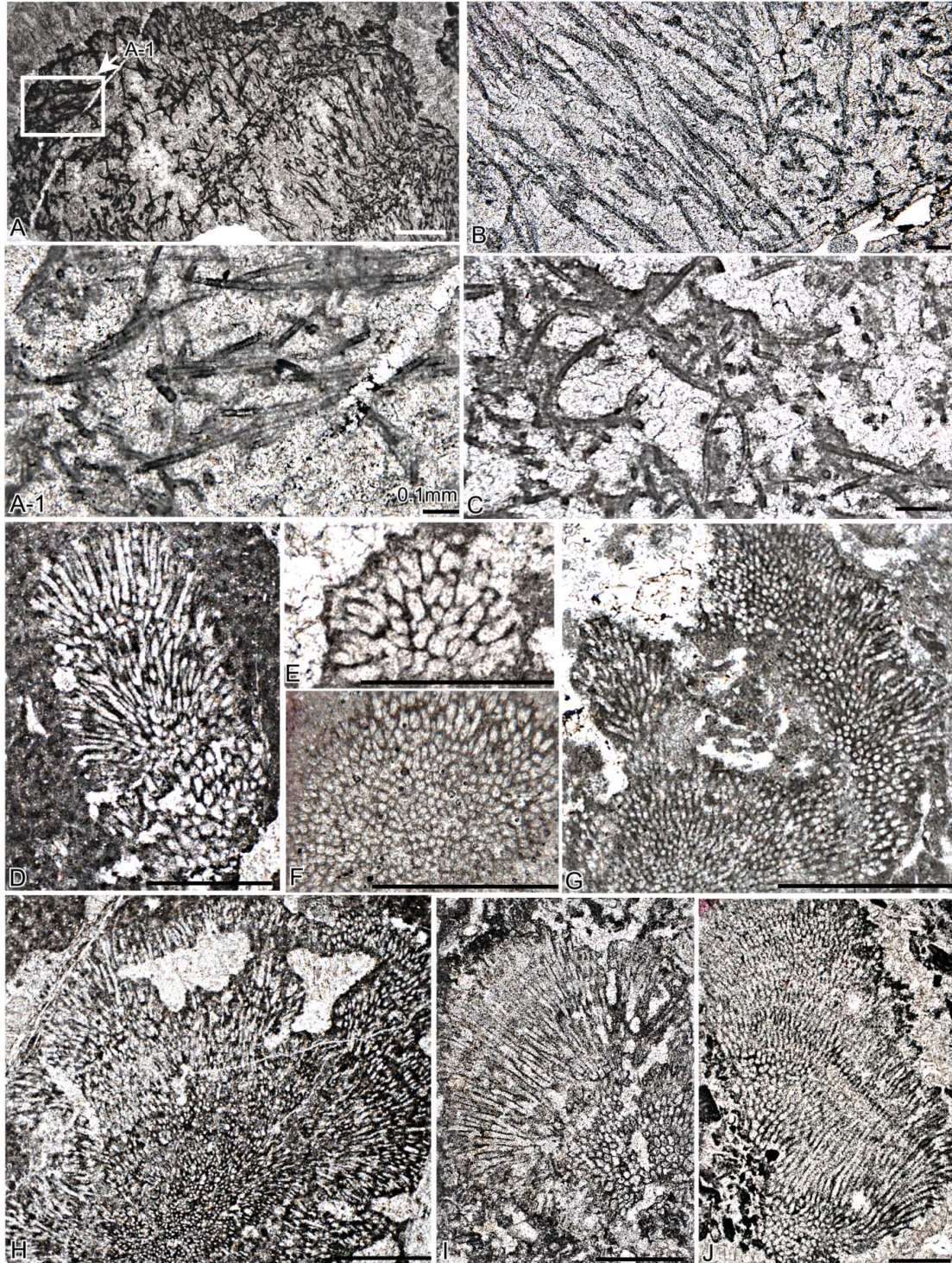


Figure 5. A–C, *Acuasiphonoria ordovica* sp. et gen. nov.; A, A-1, holotype, well TZ42, sample no. 4-53-49, C-IGGCAS, O₃l; A, overall morphology, longitudinal sections and cross sections in alternate bands; A-1, enlargement of part of A; B, 5846.35m depth, well LN63, C-PCTOC, O₃l, longitudinal sections; C, well TZ822, sample no.12-66-15, C-IGGCAS, O₃l, longitudinal and cross sections. D, *Hedstroemia halimedoidea*, well M401, sample no. 19-40-11, C-IGGCAS, O₃l, longitudinal section. E, F, *Hedstroemia bifilosa*; E, 4805.88 m depth, well TZ73, C-PCTOC, O₃l, longitudinal section; F, 4093.43 m depth, well TZ43, C-PCTOC, O₃l, longitudinal section and cross section. G, *Cayeuxia pia*, well TZ23, sample no. 9-47-36, C-IGGCAS, O₃l, longitudinal section. H, *Cayeuxia moldavica*, well M5, sample no. 19-40-29, C-IGGCAS, O₃l, longitudinal section and cross section. I, J, *Bija sibirica*; I, well TZ822, sample no. 12-66-36, C-IGGCAS, O₃l, longitudinal sections and cross sections; J, 5853.37 m depth, well LN63, C-PCTOC, O₃l, longitudinal sections and cross sections. All scale bars = 1 mm, except where indicated.

Affinity. Bornemann (1887) was the first correctly to compare *Zonotrichites* with the extant cyanobacterium *Rivularia*. Pia (1927) placed *Ortonella*, *Hedstroemia*, *Zonotrichites* and similar erect filamentous fossils in the subgroup Porostromata, under Schizophyceae. Subsequently, he attributed *Hedstroemia* and *Ortonella* to Codiaceae (Pia 1937). This latter general attribution was widely followed (Elliott 1956; Johnson & Konishi 1959; Flügel 1975; Guilbault & Mamet 1976; Bourque *et al.* 1981). However, Elliott (1964, 1975) regarded *Zonotrichites* and *Apophoretella* as calcified cyanobacteria, and Riding (1975, 1977a) argued against assignment of *Cayeuxia*, *Garwoodia*, *Hedstroemia* and *Ortonella* to Codiaceae. Luchinina (1975; in Chuvashov *et al.* 1987) attributed *Bija*, *Botomaella*, *Cayeuxia*, *Garwoodia*, *Hedstroemia* and *Ortonella* to cyanobacteria under Garwoodiaceae. Monty (1967) compared *Ortonella* with the extant cyanobacterium *Scytonema*, which was widely followed (Dragastan 1985; Riding 1991a). Dragastan (1985, 1993) insisted on the affinities between *Cayeuxia*, *Apophoretella*, *Zonotrichites* and some *Ortonella* and extant *Rivularia*, but regarded *Garwoodia* and *Hedstroemia* as pseudoudotecean green algae. Riding & Voronova (1985) and Riding (1991a, p. 67) also noted the similarities between fossil *Botomaella*, *Cayeuxia*, *Hedstroemia* and extant calcified *Rivularia*, while suggesting that fossil names should be retained for these taxa, especially since sheath calcification can preserve distinctive morphological variability (Riding 1991a, p. 78). We now regard all these taxa, with the possible exception of *Garwoodia*, as calcified sheaths of cyanobacteria similar to extant rivulariaceans (Fig. 3).

***Hedstroemia halimedoidea* Rothpletz, 1913**
(Fig. 5D)

- 1913 *Hedstroemia halimedoidea* Rothpletz: 17, pl. 3, figs 1–6.
 1976 *Hedstroemia halimedoidea* Rothpletz; Guilbault & Mamet: 644, pl. 2, figs 5–9.
 1995 *Hedstroemia* sp. Ye *et al.*: 17, pl. 9, fig. 6.
 1995 *Hedstroemia halimedoidea* Rothpletz; Mamet & Shalaby: 239, pl. 4, figs 6–10.
 1995 *Hedstroemia bernierensis* Mamet & Roux: Mamet & Shalaby: 239, pl. 4, fig. 5.
 2011 *Hedstroemia halimedoidea* Rothpletz; Liu *et al.*: 498, pl. 2, figs 5–9.

Material. Abundant in the Lianglitag Formation (O₃l) of wells M5, M401, TZ16, TZ23, TZ30, TZ35, TZ43, TZ45, TZ70, TZ72, TZ73, TZ80, TZ82, TZ83, TZ161, TZ162, TZ166, TZ241 and TZ822. These specimens often occur in micritic and peloid limestones.

Description. Tubes locally polygonal in transverse section, typically less than 80 µm in maximum diameter, with multiple branching into clusters at acute angles near 10°.

***Hedstroemia bifilosa* Rothpletz, 1913**
(Fig. 5E, F)

- 1913 *Hedstroemia bifilosa* Rothpletz: 17, pl. 3, figs 5, 6.
 1976 *Hedstroemia bifilosa* Rothpletz; Guilbault & Mamet: 644, pl. 2, fig. 4.
 1995 *Hedstroemia bifilosa* Rothpletz; Mamet & Shalaby: 239, pl. 4, fig. 11.
 2011 *Hedstroemia bifilosa* Rothpletz; Liu *et al.*: 498, pl. 2, figs 2, 3.

Material. These specimens mainly occur in association with *Hedstroemia halimedoidea*.

Description. Tubes rounded to polygonal in transverse section, ~60 µm in diameter, branching into pairs at acute angles near 10°.

Genus ***Cayeuxia* Frollo, 1938**

Type species. *Cayeuxia moldavica* Frollo, 1938; Upper Jurassic; Bicaz Gorges, East Carpathians.

Diagnosis. Calcified thallus composed of more or less loosely packed, radial, tubiform filaments. Filaments sinuous, bifurcate asymmetrically at irregular intervals. New filaments extend at an angle of nearly 45° for a short distance, becoming approximately parallel to the parent filament, expanding distally (Fig. 3).

Comparison. *Cayeuxia* resembles *Hedstroemia* in its distal expansion but differs in branching pattern. Dragastan (1985) considered *Cayeuxia* to be a junior synonym of *Rivularia*, but we retain the name *Cayeuxia* to distinguish these calcified skeletons from extant cyanobacteria whose diagnoses are based on details of soft organic tissues rather than on calcified parts (Riding 1991a).

***Cayeuxia piae* Frollo, 1938**
(Fig. 5G)

- 1938 *Cayeuxia piae* Frollo: 269, pl. 18, fig. 2.
 1986 *Hedstroemia halimedoidea* Rothpletz; Poncet: 268, pl. 4, fig. 3.
 1990 *Rivularia piae* Kuss: 67, pl. 19, figs 1, 2.

Material. Abundant in the Lianglitag Formation (O₃l) of wells TZ16, TZ23, TZ30, TZ35, TZ43, TZ73, TZ72, TZ82, TZ83, TZ166, TZ161, TZ241, M5 and M401. The specimens often occur in micritic limestones and peloid grainstones.

Description. Calcified millimetric irregular tufts of radial tubiform filaments; filaments short, sinuous, asymmetrically bifurcate, round in cross section, diameter ~30 µm.

Cayeuxia moldavica Frollo, 1938
(Fig. 5H)

1938 *Cayeuxia moldavica* Frollo: 269, pl. 18, fig. 2.

Material. These specimens mainly occur in association with *Cayeuxia piae*.

Description. Calcified millimetric elongate hemispherical tufts of radial tubiform filaments; filaments relatively long, sinuous, asymmetrically bifurcate, round in cross section, diameter ~30–40 μm .

Comparison. Very similar to *C. piae*; differing in having slightly longer filaments.

Genus *Bija* Vologdin, 1932

Type species. *Bija sibirica* Vologdin, 1932; Lower Cambrian; Siberian Platform, Russia.

Diagnosis. Calcified thallus spherical to elongate, composed of closely packed elongate tubiform filaments radiating from a base; filaments dichotomously branch at irregular intervals, mostly from the base; filament diameter declines distally (Fig. 3).

Comparison. Similar to *Hedstroemia* in its polygonal cross section (Riding & Voronova 1985) but differing in its longer and thinner filaments that decrease slightly in size distally.

Bija sibirica Vologdin, 1932
(Fig. 5I, J)

1932 *Bija sibirica* Vologdin: 16, fig. 11.

1973 *Bija sibirica* Vologdin; Korde: 37, figs 2–4; 38, figs 1, 2.

Material. Locally present in the Lianglitag Formation (O₃l) of wells TZ822, TZ24, LN63, LG621 and JF127. The specimens often occur in skeletal grainstone.

Description. Filaments, 3–5 mm long, rounded to polygonal in cross section, diameter ~100 μm at base, declining to ~40 μm distally.

Genus *Apophoretella* Elliott, 1975

Type species. *Apophoretella doburnorum* Elliott, 1975; Middle Jurassic, Great Oolite, Upper White Limestone.

Diagnosis. Calcified thallus spherical, composed of closely packed flexuous wavy branched filaments radiating from the base. Filaments long and thin; dichotomously branch at an angle of 3–4° (Fig. 3).

Comparison. Differs from *Zonotrichites* in its thinner and flexuous filaments. *Rivularia carpathica* Dragastan, 1985 is considered to be a synonym of *Apophoretella*

doburnorum. *Botomaella zelenovi* reported by Luchinina (in Chuvashov *et al.* 1987), and *Botomaella sibirica* reported by Riding & Voronova (1985), might better be placed in *Apophoretella*.

Apophoretella doburnorum Elliott, 1975
(Fig. 6A, B)

1975 *Apophoretella doburnorum* Elliott: 354, pl. 49, fig. 3.

1985 *Apophoretella doburnorum* Elliott; Dragastan: 115, pl. 16, fig. 4, 19.

1985 *Rivularia carpathica* Dragastan: 115, pl. 15, fig. 7, pl. 16, figs 1, 2.

1987 *Botomaella zelenovi* Korde; Luchinina: pl. 7, fig. 4.

1999 *Botomaella* Korde; Elicki: pl. 8, fig. 6.

Material. Locally present in the Lianglitag Formation (O₃l) of wells TZ822, TZ24, TZ241, TZ58, TZ72, TZ73, TZ161 and M401. The specimens occur in reef limestone and grainstones and packstones.

Description. Spherical calcified thallus maximally ~2 mm wide. Filaments branch at approximately the same interval, at angles of 3–4°, tending to form a banded appearance. Filament diameter 10 μm .

Genus *Ortonella* Garwood, 1914

2011 *Deisterella* Dragastan & Richter: 150, pl. 11, figs 1, 2 [new synonymy].

2011 *Springerella* Dragastan & Richter: 149, pl. 9, figs 1–4 [new synonymy].

Type species. *Ortonella furcata* Garwood, 1914; Lower Carboniferous; Westmoreland, England.

Diagnosis. Calcified thallus, rounded or nodular, consisting of ramifying calcareous filaments radiating from the base. Filaments circular, dichotomously branched at angles between ~25° and 40° (Fig. 3).

Remarks. The genus *Botomaella* closely resembles *Ortonella*. *Springerella* Dragastan & Richter, 2011 and *Deisterella* Dragastan & Richter, 2011 closely resemble *Ortonella* and we regard them as junior synonyms. Some *Dimorphosiphonoides*, possibly an Ordovician calcareous green algae (reported by Guilbault & Mamet 1976; Liu *et al.* 2011), has been misidentified as *Ortonella* (Kwon *et al.* 2012, fig. 5D).

Ortonella furcata Garwood, 1914
(Fig. 6D)

1914 *Ortonella furcata* Garwood: 265, pl. 20, figs 1–4.

1990 *Ortonella furcata* Garwood; Bian & Zhou: pl. 1, fig. 6.

1995 *Ortonella furcata* Garwood; Ye *et al.*: 16, pl. 8, fig. 8.

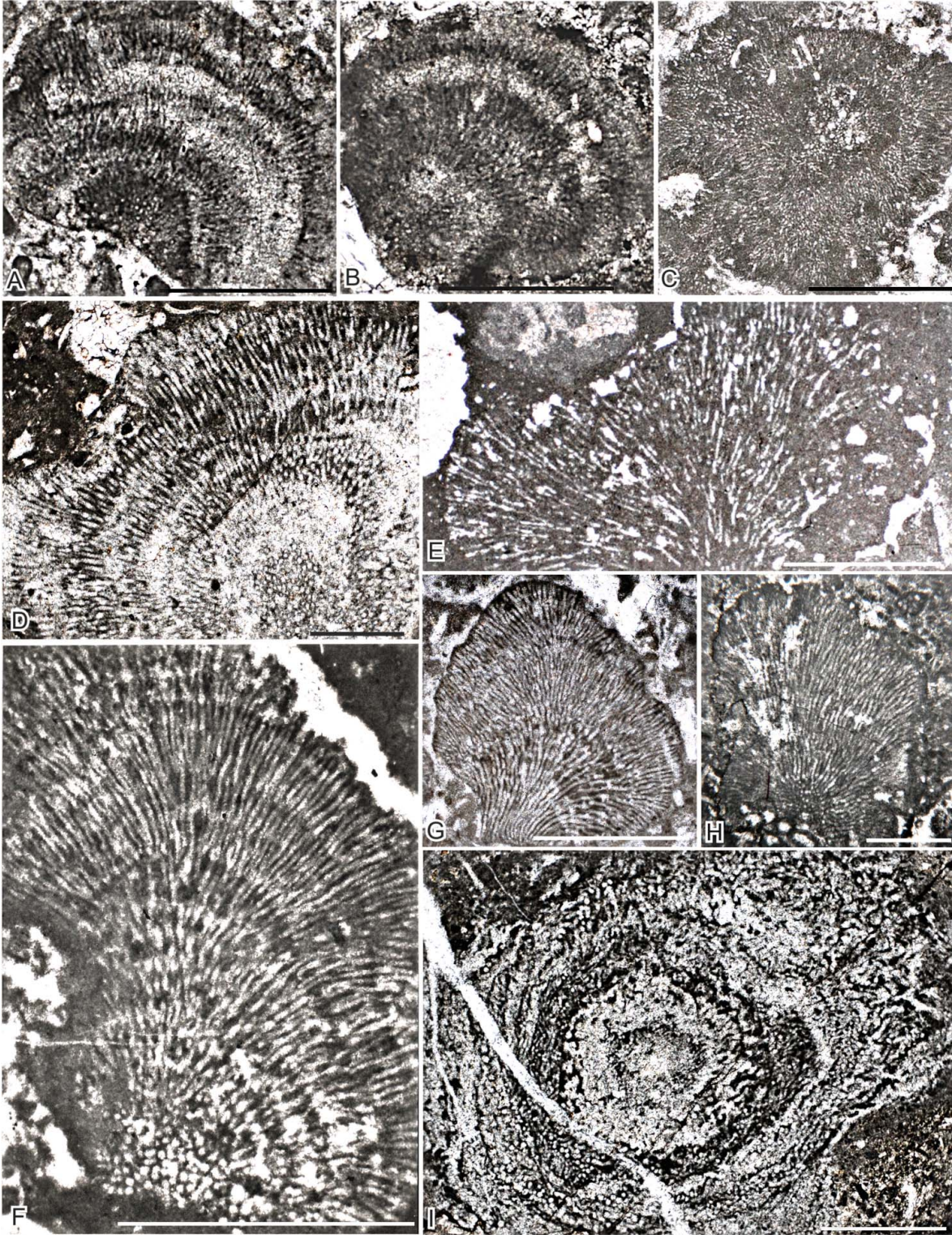


Figure 6. **A, B**, *Apophoretella doburnorum*; **A**, well TZ73, sample no. 6-79-31, C-IGGCAS, O₃l, longitudinal and cross section; **B**, well TZ58, sample no. 13-46-15, C-IGGCAS, O₃l, longitudinal section and cross section. **C**, *Ortonella tenuissima*, 4311.04 m depth, well TZ161, C-PCTOC, O₃l, longitudinal section. **D**, *Ortonella furcata*, well HE3, sample no. 12-48-47, C-IGGCAS, O₃l, longitudinal section. **E**, *Ortonella kershopenensis*, 5136.04 m depth, well TZ80, C-PCTOC, O₃l, longitudinal section. **F–H**, *Zonotrichites lissaviensis*; **F**, well S6, sample no. 1-51-3, C-IGGCAS, O₃l, longitudinal sections; **G**, well M5, sample no. 20-37-32, C-IGGCAS, O₃l, longitudinal section; **H**, 4943.54 m depth, well TZ70, C-PCTOC, O₃l, longitudinal sections. **I**, *Bevoacstria conglobata*, well TZ23, sample no. 9-47-5, C-IGGCAS, O₃l, longitudinal section. All scale bars = 1 mm.

2009 *Ortonella* Wang *et al.*: fig. 2f.

2011 *Ortonella* sp. 2 Liu *et al.*: 498, pl. 2, fig. 1.

Material. Abundant in the Lianglitag Formation (O₃l) of wells TZ43, TZ166, TZ161, TZ241, TZ16, TZ73, TZ83, TZ23, TZ63, TZ451, TZ35, TZ826, TZ822, M401 and HE3. Specimens mainly occur in micritic and peloid limestones and rarely as the cores of oncolites.

Description. Thallus small, rounded, nodular, ~5 mm across; filaments slightly undulose, dichotomously branched at ~30° at various intervals, diameter 38–55 µm.

Ortonella tenuissima Garwood, 1931
(Fig. 6C)

1931 *Ortonella tenuissima* Garwood: 138, pl. 14, fig. 2C₁.

Material. Locally present in the Lianglitag Formation (O₃l) of well TZ161. Specimens occur in skeletal grainstones.

Description. Thallus irregular, up to 2.5 mm across; filaments slightly undulose, dichotomously branched at ~30°, at various intervals, diameter narrow, ~7 µm.

Ortonella kershopensis Garwood, 1931
(Fig. 6E)

1931 *Ortonella kershopensis* Garwood: 138, pl. 13, fig. 3, pl. 14, fig. 1C₂.

1986 *Ortonella mansellesis* Poncet: 268, pl. 4, figs 4, 5.

1990 *Rivularia fruticulosa* Kuss: 67, pl. 19, figs 3, 4.

1995 *Ortonella kershopensis* Garwood; Mamet & Shalaby: 239, pl. 4, fig. 12.

2011 *Ortonella* sp. 1 Liu *et al.*: 499, pl. 3, figs 3, 4.

Material. Abundant in the Lianglitag Formation (O₃l) of wells TZ80, TZ43, TZ166, TZ161, M401, TZ241, TZ16, TZ73, HE3, TZ83, TZ23, TZ63, TZ451 and TZ35. Specimens mainly occur in micritic and peloid limestones.

Description. Thallus irregularly rounded, ~2.5 mm across, filaments slightly undulose, dichotomously branched at 25–50°, filament diameter ~20–30 µm.

Genus *Zonotrichites* Bornemann, 1887

1990 *Ortonellina* Bian & Zhou: 5, pl. 2, fig. 6.

Type species. *Zonotrichites lissaviensis* Bornemann, 1987; Upper Triassic; Poland.

Diagnosis. Calcified subrounded thallus composed of slightly curved, closely packed, elongate filaments of uniform diameter, radiating from a small base. Filaments branch dichotomously at angles less than 20°; subparallel after branching (Fig. 3).

Comparison. Similarity to *Ortonella* may have led to misidentification. For example, the Ordovician specimen attributed to *Ortonella* by Guilbault & Mamet (1976, pl. 1, figs 1–4, 6, 7), can be regarded as *Zonotrichites*, as might the *Ortonella* of Mamet & Roux (1975) from the Devonian and Carboniferous. The Ordovician genus *Ortonellina* erected by Bian & Zhou (1990) can be regarded as a junior synonym of *Zonotrichites*. *Zonotrichites* differs from *Ortonella* in generally smaller branching angle, smaller diameter, and closely appressed filaments. Dragastan (1985) considered *Zonotrichites* to be a junior synonym of *Rivularia*, but we retain the name *Zonotrichites* to distinguish these calcified skeletons from extant cyanobacteria whose diagnoses are based on details of soft organic tissues and not on hard parts (Riding 1991).

Zonotrichites lissaviensis Bornemann, 1887
(Fig. 6F–H)

1887 *Zonotrichites lissaviensis* Bornemann: 5, figs 1, 2, pl. 4, figs 1, 2.

1964 *Zonotrichites lissaviensis* Bornemann; Elliott: pl. 1, figs 1, 2, pl. 2, figs 1–3.

1972 *Hedstroemia* Walker: fig. 14F, G.

1976 *Ortonella aequalis* (Høeg); Guilbault & Mamet: pl. 1, figs 1–4, 6, 7.

1990 *Ortonellina zhuzhaiensis* Bian & Zhou: 6, pl. 2, fig. 6.

1995 *Ortonella aequalis* (Høeg); Mamet & Shalaby: pl. 4, figs 1–3.

2001 *Botomaella aequalis* (Høeg); Riding & Fan: 787, text-fig. 3A.

Material. Abundant in the Lianglitag Formation (O₃l) of wells of S6, TZ70, TZ43, TZ166, TZ162, TZ161, TZ241, TZ16, TZ73, TZ72, TZ83, TZ23, TZ45, TZ63, TZ451, TZ23, TZ35, TZ30, TZ35, TZ82, TZ822, M401 and M5. Specimens mainly occur in micritic and peloid limestones and rarely in skeletal grainstones.

Description. Thallus irregular to subrounded, ~2–3 µm across, filaments bifurcate uniformly, producing a concentric appearance in longitudinal section. Filament diameter ~20–50 µm.

Genus *Bevocastria* Garwood, 1931

Type species. *Bevocastria conglobata* Garwood, 1931; Lower Carboniferous; England.

Diagnosis. Calcareous tubular filaments, sinuous, constricted at intervals, forming closely and irregularly interlaced encrusting mats (Fig. 3).

Affinity. *Bevocastria* was regarded as a calcified cyanobacterium by Riding (1991a) (Fig. 3).

Bevocastria conglobata Garwood, 1931
(Fig. 6I)

1931 *Bevocastria conglobata* Garwood: 19, pl. 12, figs 1–3.

1981 *Bevocastria conglobata* Bourque *et al.*: 96, pl. 2, fig. 5, pl. 4, fig. 7, pl. 5, figs 2, 4–7.

2001 *Bevocastria* sp. Riding & Fan: 300, pl. 3, figs 1, 2.

Material. Locally present in the Lianglitag Formation (O₃l) of well TZ23. The specimens occur in packstones.

Description. Tubes averaging 40 µm in diameter, disposed in irregular concentric bands.

?Cyanobacteria

Genus ***Proaulopora*** Vologdin, 1937

1957 *Vologdinella* Korde: 70.

1959 *Amganella* Reitlinger: 62.

Type species. *Proaulopora rarissima* Vologdin, 1937; Lower Cambrian; Siberia Platform.

Diagnosis. Calcified tubes, occasionally branched; wall micritic, apparently layered. Short whorl-like external collars extend from the outer surface at an acute angle, and are concentric in cross section (Fig. 3).

Comparison. *Vologdinella* and *Amganella* are junior synonyms of *Proaulopora* (e.g. Voronova 1976). *Proaulopora* differs from *Phacelophyton* in its short whorl-like external collars. Some reports of *Proaulopora* from the Cambrian (Elicki 1999; Javier *et al.* 2006) resemble *Phacelophyton* in their smaller tube diameter and absence of external collars.

Affinity. Vologdin (1937) and Korde (1961, 1973) suggested that *Proaulopora* is a red alga. Luchinina (1975; in Chuvashov *et al.* 1987) compared *Proaulopora* with the extant cyanobacterium *Calothrix gypsophila*, a rivulariacean with collar-like projections of the sheath, although she noted that the diameter of *Proaulopora* is twice that of *Calothrix*. *Proaulopora* also resembles some species of another extant rivulariacean, *Dichothrix*, which has a thick laminated sheath (containing more than one trichome) with collar-like projections (Fig. 3). We regard *Proaulopora* as a probable cyanobacterium.

Proaulopora rarissima Vologdin, 1937
(Fig. 7A, B)

1937 *Proaulopora rarissima* Vologdin: 21, pl. 3, fig. 13.

1975 *Proaulopora rarissima* Vologdin; Luchinina: 26, pl. 23, figs 1, 2, pl. 24, figs 1–4.

1973 *Proaulopora flexuosa* Korde: 226, pl. 33, figs 3, 4, pl. 36, fig. 5.

1995 *Proaulopora* sp. Ye *et al.*: 19, figs 3, 5.1–5.3.

Material. Present in packstones of the Yingshan Formation (O₁₋₂y) of well TZ63, and reef limestones and packstones of the Lianglitag Formation (O₃l) of wells TZ24, TZ822, TZ241, LN63 and JF127.

Description. Tubes relatively long, up to 3 mm; external diameter ~100–230 µm; wall thickness ~20–30 µm.

Proaulopora pachydermatica sp. nov.
(Fig. 7C, D)

2011 *Proaulopora* sp. Liu *et al.*: 500, pl. 4, figs 2–4.

Material. Holotype: thin section 4-36-27, well TZ241, housed in the C-IGGCAS; Upper Ordovician Katian Stage (Lianglitag Formation); Tarim Basin, Xinjiang Province, Northwest China. Present in grainstones of the Yijianfang Formation (O₂y) of well GC4 and reef limestones, grainstones and packstones of the Lianglitag Formation (O₃l) of wells TZ24, TZ822 and TZ241.

Etymology. *pachy-* meaning thick; *dermatica* meaning dermal.

Description. Tubes relatively short, up to 1 mm long, with thick walls; external diameter ~100–230 µm, wall thickness 70–160 µm.

Comparison. This new species differs from other *Proaulopora* species in its thick wall and relatively short tubes.

Genus ***Phacelophyton*** Bian & Zhou, 1990

Type species. *Phacelophyton yushanensis* Bian & Zhou, 1990; Upper Ordovician; South China.

Diagnosis. Calcified tubes; elongate, straight to gently curved, branched at acute angles ~25°; micritic wall, ‘sheath-within-sheath’ interlayered structure creates a relatively thick laminate wall, with smooth interior surface and irregularly patterned external surface, and a diffuse swirl-like appearance in cross section (Fig. 3).

Comparison. Differs from *Proaulopora* in the absence of whorl-like external collars and presence of pronounced sheath-within-sheath wall structure (Fig. 3).

Affinity. Bian & Zhou (1990) regarded *Phacelophyton* as a cyanobacterium based on the similarities of its laminated wall to the multilayer sheaths of some extant cyanobacteria. It has some resemblance to present-day *Calothrix* (Fig. 3). We regard *Phacelophyton* as a probable cyanobacterium.

Phacelophyton yushanensis Bian & Zhou, 1990
(Fig. 7E–H)

1990 *Phacelophyton yushanensis* Bian & Zhou: 6, pl. 3, figs 4, 5, 7.

1995 *Phacelophyton* sp. Ye *et al.*: 16, pl. 9, figs 1, 2.

2011 *Phacelophyton* sp. Liu *et al.*: 501, pl. 4, fig. 5.

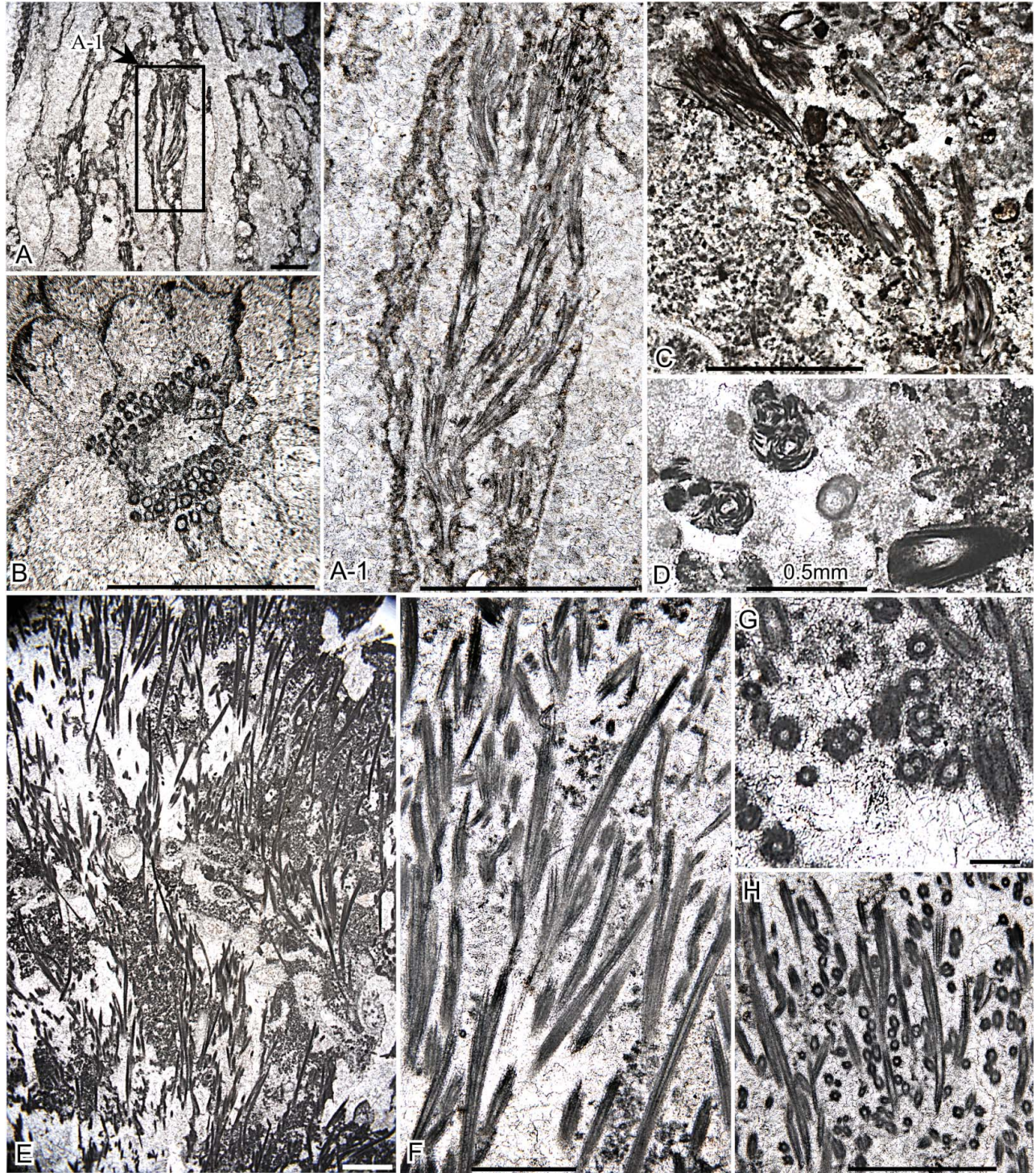


Figure 7. **A, B,** *Proaulopora rarissima*; **A, A-1,** well TZ24, sample no. 16-35-15, C-IGGCAS, O₃l, longitudinal section, **A-1,** an enlargement of part of **A**; **B,** 4621.16 m depth, well TZ24, C-PCTOC, O₃l, cross section. **C, D,** *Proaulopora pachydermatica* sp. nov.; **C,** holotype, well TZ241, sample no. 4-36-27, C-IGGCAS, O₃l, longitudinal section; **D,** well GC4, sample no. 2-52-4, C-IGGCAS, O₂y, cross section. **E–H,** *Phacelophyton yushanensis*, well TZ822, sample no. 12-66-57, C-IGGCAS, O₃l; **E,** overall morphology; **F,** longitudinal sections; **G,** cross sections. All scale bars = 1 mm, except where indicated.

Material. Present in reef limestones in the Lianglitag Formation (O₃l) of well TZ822, TZ24, LN63, LN621, TZ42, and LG391.

Description. Overall thallus up to 10 mm wide and 15 mm high; filaments gently curved, external diameter ~50 µm, internal diameter ~16 µm.

Genus *Gomphosiphon* gen. nov.

Type species. *Gomphosiphon xinjiangensis* sp. nov.; Upper Ordovician, Katian Stage (Lianglitag Formation); Xinjiang Province, Northwest China.

Etymology. *Gompho* meaning a bundle; *siphon* meaning tubules.

Diagnosis. Long gently curved calcified tubes, branching at acute angles, about 15–20°. Wall micritic, laminated, with a diffuse swirl-like appearance in cross section (Fig. 3).

Comparison. This new monospecific genus closely resembles *Phacelophyton* in its laminate wall structure, but differs in its thinner walls and closely spaced inter-laced tube arrangement.

Affinity. We compare this genus with rivulariaceans such as the extant *Calothrix* (Fig. 3), as for *Phacelophyton*.

Gomphosiphon xinjiangensis gen. et sp. nov.
(Fig. 8)

Material. Holotype: thin section from a depth of 5852.74 m in well TZ822, housed in the C-PCTOC; Upper Ordovician Katian Stage (Lianglitag Formation); Tarim Basin, Xinjiang Province, Northwest China. Locally present in reef limestones and packstones in the Lianglitag Formation (O₃l) of wells LN621 and TZ822.

Etymology. The species is named after Xinjiang Province where it was first found.

Diagnosis. As for the genus.

Description. Tubes tangled into loose and irregular strands (Fig. 8A, B). Tube length ~6 mm, external diameter ~60–100 µm.

Calcified Microproblematica
Genus *Renalcis* Vologdin, 1932

1957 *Nephelostroma* Dangeard & Doré: 1070.

Type species. *Renalcis granosus* Vologdin, 1932; Middle Cambrian; Altai Mountains, Russia.

Diagnosis. Calcareous microfossil; hollow rounded and lunate chambers in botryoidal clusters with short branches; chambers wider than high, mutually overlapping; wall micritic, moderately thick, may contain clefts on inner surface; smooth well-defined outer and inner surfaces (Fig. 3).

Comparisons. *Nephelostroma* is considered to be a synonym of *Renalcis* (Reitlinger 1960). *Renalcis* has similarities with *Chabakovia*, *Izhella*, *Shuguria*, *Gemma* and *Tarthinia*. These fossils have been attributed to the Family Chabakoviaceae (Korde 1973; Luchinina in Chuvashov *et al.* 1987) and to the *Renalcis* Group (Riding 1991a).

Affinity. Korde (1961, 1973), Maslov & Korde (1963) and Saltovskaya (1975) all regarded *Renalcis* as a cyanobacterium. Hofmann (1975, p. 1131) suggested *Renalcis* might “represent remains of peripherally pigmented, gelatinous colonies of Chroococcalean algae which have undergone carbonate diagenesis involving obliteration of cell morphology”. This view was supported by Pratt (1984). Luchinina (in Chuvashov *et al.* 1987) regarded *Chabakovia*, *Renalcis*, *Izhella* and *Angulocellularia* as chroococcaleans and compared *Renalcis* with *Microcystis*. A cyanobacterial affinity for *Renalcis* was favoured by Riding (1991a) and Turner *et al.* (2000). Chafetz & Guidry (1999) considered that *Renalcis* (and *Epiphyton*) could be produced by precipitation induced by communities of phototrophic and heterotrophic bacteria. Similarly, Stephens & Sumner (2002) proposed that *Renalcis* could be fossilized biofilm clusters which calcified due to heterotrophic bacterial activity. We regard *Renalcis* and similar genera as possible bacterial calcified Microproblematica (Fig. 3).

Renalcis granosus Vologdin, 1932
(Fig. 9A)

1932 *Renalcis granosus* Vologdin: 15, pl. 9.

1972 *Renalcis* sp. Riding & Toomey: 514, pl. 2, figs 1–3.

1990 *Renalcis devonicus* Bian & Zhou: pl. 1, figs 2, 5.

1995 *Renalcis* sp. Ye *et al.*: 15, pl. 8, fig. 6.

2009 *Renalcis* Vologdin; Wang *et al.*: fig. 2d.

2009 *Izhella* Antropov; Wang *et al.*: fig. 2e.

Material. Locally present in microbial limestones of the Yijianfang Formation (O₂y) of well GC4, and abundant in reef limestone of the Lianglitag Formation (O₃l) of wells TZ42, TZ822, ZG171, LN63, LG391 and JF127.

Description. Composed of branches of superposed chambers arising from a common base. Chambers relatively large, with external diameter of 200–500 µm. Walls ~50 µm thick, locally with poorly developed clefts on inner surface.

Renalcis seriata Korde, 1961
(Fig. 9B)

1961 *Renalcis seriata* Korde: pl. 2, fig. 3.

2011 *Renalcis* Wang *et al.*: pl. 1, fig. 7.

2011 *Renalcis* sp. Liu *et al.*: 144, pl. 3, fig. 6.

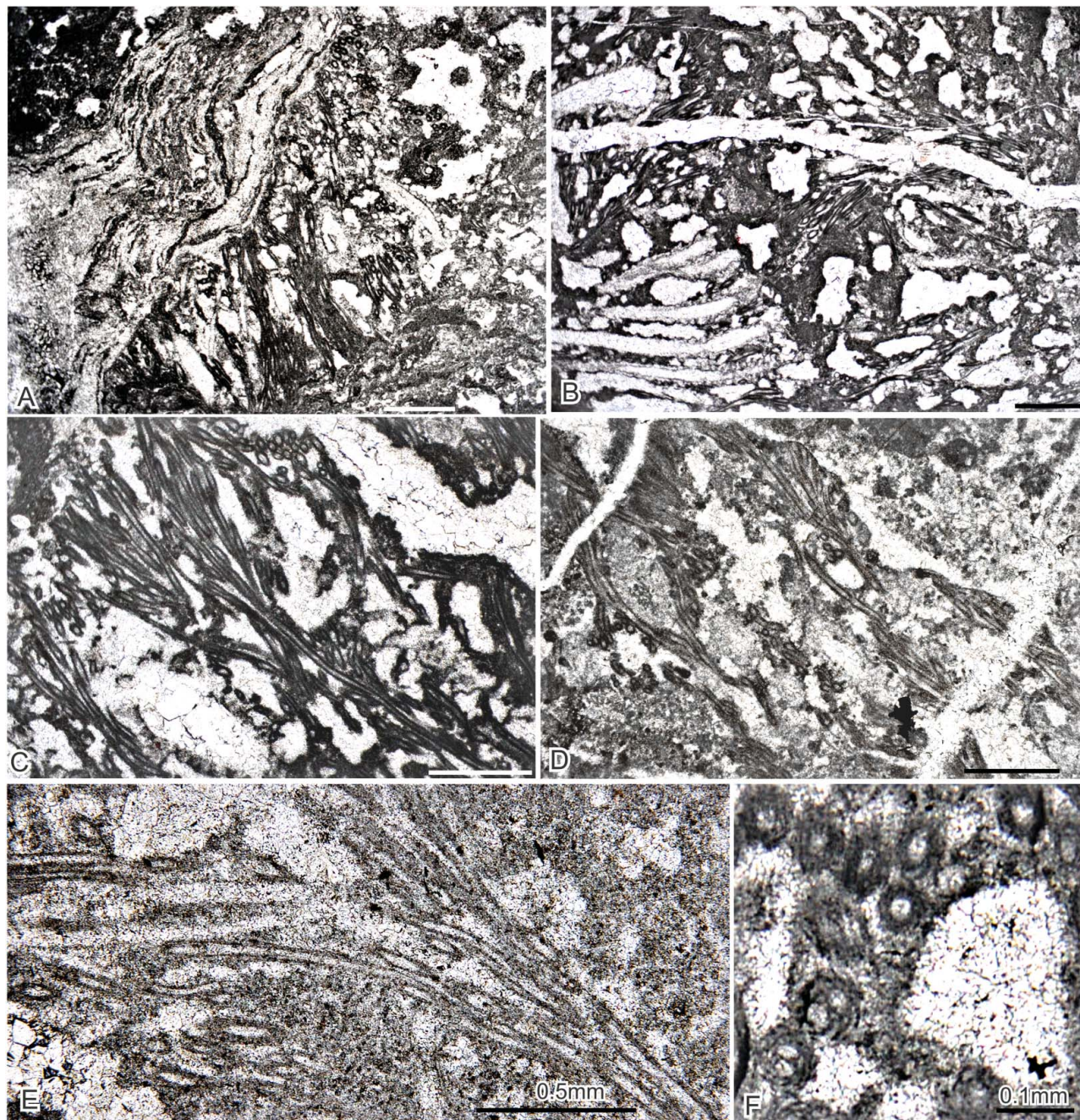


Figure 8. *Gomphosiphon xinjiangensis* gen. et sp. nov. **A**, well TZ822, sample no. 12-66-41, C-IGGCAS, O₃l, longitudinal section and cross section. **B**, 5852.74 m depth, well TZ822, C-PCTOC, O₃l, longitudinal section and cross section. **C**, holotype, 5852.74 m depth, well TZ822, C-PCTOC, O₃l, longitudinal section and cross section. **D**, well LN621, sample no. 2-52-22, C-IGGCAS, O₃l, longitudinal section and cross section. **E**, well TZ822, sample no. 12-66-32, C-IGGCAS, O₃l, longitudinal sections. **F**, well TZ822, sample no. 11-66-36, C-IGGCAS, O₃l, cross section. All scale bars = 1 mm, except where indicated.

Material. Abundant in the Lianglitag Formation (O₃l) of wells TZ42, TZ822, ZG171, LN63, LG391 and JF127. Specimens mainly occur in reef limestone.

Description. Chambers irregular, spherical to hemispherical, arranged in short to elongate relatively narrow irregular branches that diverge at low angles. Chambers ~200

µm in external diameter; wall thickness ~50 µm, variable.

Comparison. With their narrow branches, some specimens resemble *Chabakovia*, described by Vologdin (1939). However, *Chabakovia* is distinguished by its more inflated and thinner-walled chambers.

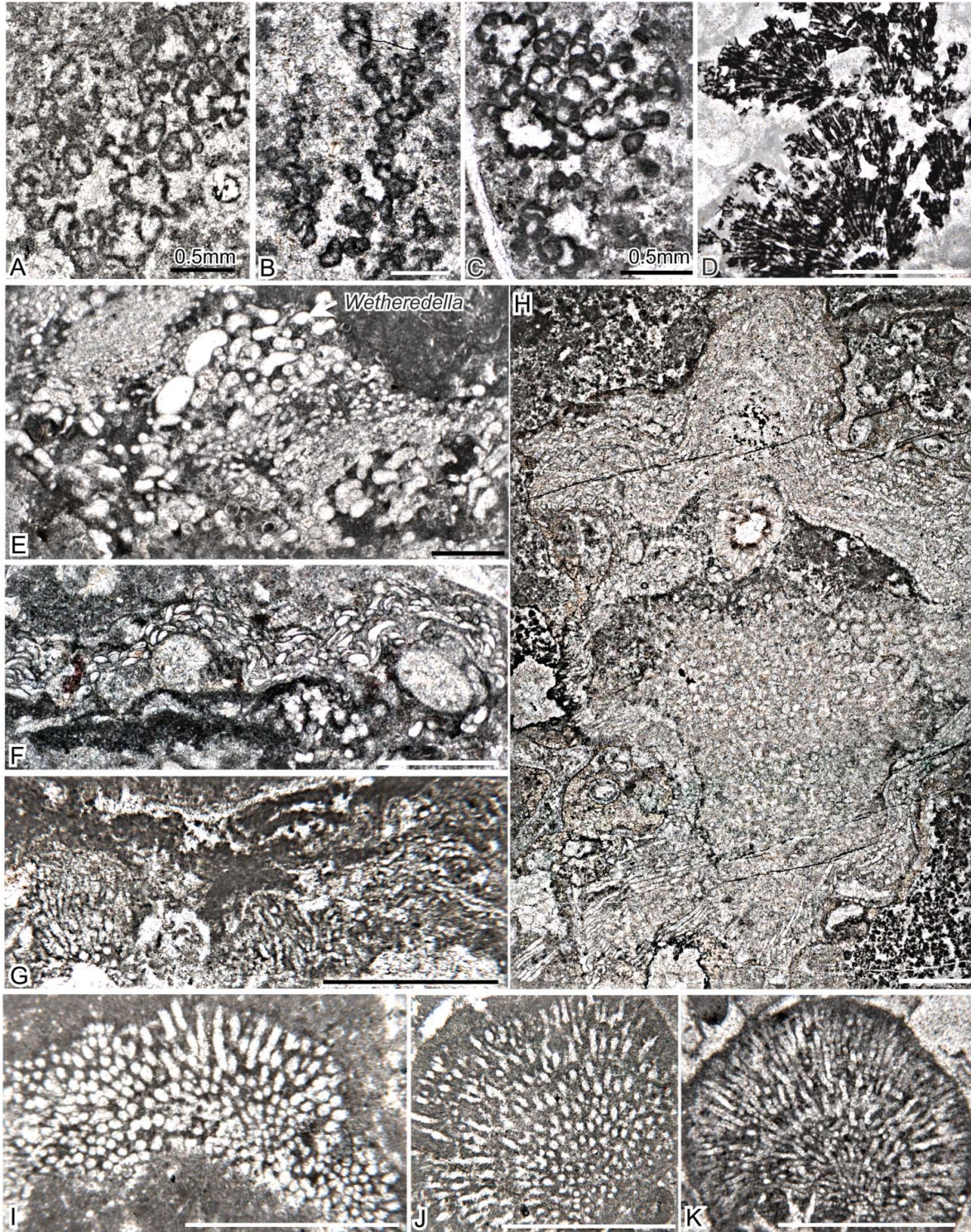


Figure 9. **A**, *Renalcis granosus*, well TZ822, sample no. 12-66-27, C-IGGCAS, O₃l, oblique cross section. **B**, *Renalcis seriata*, well JF127, sample no. 13-20-10, C-IGGCAS, O₃l, mainly longitudinal section. **C**, *Izhella nubiformis*, 5854.66 m depth, well TZ822, sample no. 12-66-48, C-IGGCAS, O₃l, oblique longitudinal section. **D**, *Epiphyton* sp., well GC4, sample no. 6-48-33, C-IGGCAS, O₂y. **E**, **F**, *Wetheredella silurica*; **E**, well TK1, sample no. 15-35-10, C-IGGCAS, O₂y, longitudinal section; **F**, 5356.96 m depth, well LN14, C-PCTOC, O₃l, longitudinal section. **G**, *Rothpletzella gotlandica*, 5967.06 m depth, well TZ63, C-PCTOC, O₃l, longitudinal and cross sections. **H**, *Rothpletzella longita* sp. nov., holotype, 5684.50 m depth, well TZ822, C-PCTOC, O₃l, longitudinal and cross section. **I**, **J**, *Garwoodia gregaria*; **I**, 4091.75 m depth, well TZ43, C-PCTOC, O₃l, longitudinal and cross section; **J**, 5454.06 m depth, well TZ83, C-PCTOC, O₃l, longitudinal and cross section. **K**, *Garwoodia americana*, 4398.92 m depth, well TZ161, C-PCTOC, O₃l, longitudinal and cross section. All scale bars = 1 mm, except where indicated.

Genus *Izhella* Antropov, 1955

Type species. *Izhella nubiformis* Antropov, 1955; Upper Devonian; Russia.

Diagnosis. Chambered microfossil forming compact botryoidal clusters from which short branches arise; wall lunate, thick, micritic, with deep clefts extending through about two-thirds of the wall thickness and opening toward the inner surface (Fig. 3).

Comparison. *Izhella* closely resembles *Renalcis* (see Riding 1991a; Feng *et al.* 2010), within which it has often been subsumed. For example, Wray (1967) named Devonian specimens of *Izhella* in the Canning Basin as *Renalcis turbitus*, and Korde (1973) named Cambrian specimens of *Izhella* in the Siberia platform *Renalcis tuberculatus*. The chamber wall of *Izhella* is typically thick and has deep narrow clefts on the inner surface, whereas the walls in *Renalcis* are generally thinner and clefts are poorly developed or absent.

Affinities. See *Renalcis*. We regard *Izhella* and similar genera as possible bacterial calcified Microproblematica (Fig. 3).

Izhella nubiformis Antropov, 1955
(Fig. 9C)

- 1955 *Izhella nubiformis* Antropov: 47.
1967 *Renalcis turbitus* Wray: 46, pl. 11, fig. 1.
1983 *Renalcis* Adams: 330, figs 1, 2.
1973 *Renalcis tuberculatus* Korde: 113, pl. 3, fig. 1.
2011 *Izhella* sp. Liu *et al.*: 501, pl. 5, fig. 5.

Material. These specimens mainly occur in association with *Renalcis* in the Lianglitag Formation (O₃l).

Description. Basal chambers up to 0.5 mm in external diameter, with compound lobate cavity ~0.3 mm wide, walls ~0.1 mm thick with clefts up to 30 µm deep. Short radial stems have small ovoid to reniform chambers.

Genus *Epiphyton* Bornemann, 1886

Type species. *Epiphyton flabellatum* Bornemann, 1886; Lower Cambrian; Sardinia, Italy.

Description. Calcified dendritic microfossil, filaments circular, typically micritic, diameter can increase slightly distally, branching often dichotomous at relatively small angles ~20° (Fig. 3).

Comparison. Korde (1973) created many genera similar to *Epiphyton*, which may include junior synonyms (Riding 1991b). Even so, several similar but distinct genera can be distinguished (e.g. *Korilophyton*, *Gordonophyton*, *Tharama*, *Tubomorphophyton*) which have been variously attributed to the Family Epiphytaceae (Korde 1959, 1973;

Chuvashov *et al.* 1987) or to the *Epiphyton* Group (Riding 1991a).

Affinity. Early researchers suggested a chlorophyte (Bornemann 1886) or cyanobacterial (Pia 1927, p. 39) affinity for *Epiphyton*. Korde (1959, 1973) regarded *Epiphyton* as a red alga on the basis of cell structure that she identified in some filaments. This attribution was followed by Vologdin (1962), Johnson (1996b) and Chuvashov (in Chuvashov *et al.* 1987, p. 127). *Epiphyton*, *Renalcis* and similar genera often co-occur. Saltovskaya (1975) suggested that epiphytaceans and chabakoviaceans show intergradation, reflecting mutual affinity of these genera. Morphological intergradation between these fossils was documented by Pratt (1984) and Riding & Voronova (1985). Pratt (1984) suggested that *Epiphyton* is a diagenetic microfossil produced by coccoid cyanobacteria, similar to some interpretations of *Renalcis*. Riding & Voronova (1985) pointed out that transitions may reflect morphological convergence rather than systematic affinity. Luchinina (1975; in Chuvashov *et al.* 1987, p. 23) attributed *Renalcis* to Chroococcales and *Epiphyton* to Hormogonophyceae. Riding & Voronova (1982) noted that some stigonemataleans closely resemble epiphytaceans. Luchinina (2009) suggested that *Renalcis* and *Epiphyton* represent different stages in algal life cycles. Laval *et al.* (2000) reported a distinctive assemblage of freshwater calcite microbialites in Pavilion Lake, British Columbia, Canada, some of which display microstructures similar to fabrics displayed by *Epiphyton* and *Girvanella*. However, Luchinina & Terleev (2008) compared exceptionally preserved *Epiphyton* with the extant red alga *Corallina*, although *Epiphyton* is smaller in size and lacks some features present in *Corallina*. Woo & Chough (2010) presented evidence of phototropism in Middle Cambrian *Epiphyton* from China, and regarded them as photosynthetic microbial colonies. We regard *Epiphyton* as a Microproblematicum (Fig. 3).

Remarks. There are numerous species of *Epiphyton*, many described by Korde (1961) from the Lower Cambrian of the Siberian Platform; most are based on subtle details of the microstructure or slight differences in angle of branching and are difficult to distinguish with confidence (Riding 1991a). Luchinina (1975) revised the genus and divided it into 13 species.

Epiphyton sp.
(Fig. 9D)

Material. Locally present in the Yijianfang Formation (O₂) of well GC4. The specimens occur in microbial limestone.

Description. Filaments closely spaced, slightly sinuous to irregular, forming tree-like radiating clusters up to

4 mm across; branching is at $\sim 10\text{--}15^\circ$; filament diameter $\sim 40\text{--}50\ \mu\text{m}$.

Remarks. This *Epiphyton* appears to have tubiform and/or chambered filaments. It can therefore be compared with *Tubomorphophyton* (see Riding & Voronova 1982).

Genus *Wetheredella* Wood, 1948

Type species. *Wetheredella silurica* Wood, 1948; Lower Silurian; England.

Diagnosis. Aggregations of calcified encrusting tubes, hemispherical to reniform in transverse section (Fig. 3).

Affinity. The affinity of *Wetheredella* has long been debated. It has variously been suggested to be a foraminifer (Wood 1948), cyanobacterium (Copper 1976), and green alga (Mamet & Roux 1975; Ishchenko & Radionova 1981; Chuvashov *et al.* 1987). Copper's (1976) view that *Wetheredella* is a cyanobacterium was challenged by Riding (1977b), who considered it a Microproblematicum (Riding 1991a). Based on present-day material, Kaźmierczak & Kempe (1992, 2004) proposed that structures similar to *Wetheredella* may be produced by calcification of aggregates of colonies of pleurocapsalean cyanobacteria. Recently, *Wetheredella* has been assigned to the *incertae sedis* group Algospongia (Vachard & Cozar 2010), and compared with the similarly problematical fossil *Allonema* (Munnecke & Jarochowska 2014). It is possible that *Wetheredella* is a synonym of *Allonema* Ulrich & Bassler 1904 (Jarochowska & Munnecke 2014). We regard *Wetheredella* as a Microproblematicum (Fig. 3).

Wetheredella silurica Wood, 1948
(Fig. 9E, F)

1948 *Wetheredella silurica* Wood: 20, pl. 3, fig. B, pl. 5, fig. B.

1976 *Wetheredella tumulus* Copper: 277, pl. 1, figs B, C.

2011 *Wetheredella silurica* Wood; Liu *et al.*: 502, pl. 3, fig. 1.

Material. Present in reef limestone in the Yijianfang Formation (O_{2y}) of wells TK1 and HA902, reef limestone and oncolites in the Lianglitag Formation (O_{3l}) of wells TZ822, TZ826, TZ242, TZ30, TZ72, TZ58, TZ63, TZ82, TZ83, TZ161, M401 and M5, and in oncolites in the Sangtamu Formation (O_{3s}) of wells TZ35, LN46, YW2 and HE3.

Description. Calcified tubes irregularly reniform and hemispherical in cross section, closely packed and irregularly stratiformly arranged; 100–250 μm in size. Wall thin, $\sim 50\ \mu\text{m}$.

Comparison. We regard *Wetheredella tumulus* Copper, 1976 as a junior synonym of *Wetheredella silurica* because of their close similarity. Differences in size are relatively slight, especially considering the essentially tubiform nature of this fossil. Copper (1976, p. 280) noted that the variability in tube diameter and ability to form mounds in *W. tumulus* could in part be a response to ecological factors, and we do not consider these sufficient specific characters. Some of our Tarim specimens are larger, up to 750 μm in width (Fig. 9F), than is usual for *W. silurica*.

Genus *Rothpletzella* Wood, 1948

1890 *Sphaerocodium* Rothpletz: 9.

1956 *Coactilum* Maslov: 28, pl. 3, text-fig. 3.

Type species. *Rothpletzella gotlandica* (Rothpletz) Wood, 1948; Silurian, Wenlock and Woolhope Limestones; England and Sweden.

Diagnosis. Calcareous tubular filaments, prostrate, bifurcating to form sheet-like flat to undulose layers, resembling strings of beads in transverse section. Wall thin, micritic (Fig. 3).

Comparison. *Sphaerocodium*, recorded by Rothpletz (1890) from the Wenlockian of Gotland, Sweden, was shown by Wood (1948) to be an intergrowth of *Rothpletzella* and *Wetheredella* (see also Riding & Fan 2001, p. 804). *Coactilum* Maslov, 1956 is a junior synonym of *Rothpletzella*.

Affinity. *Rothpletzella* has been regarded as a cyanobacterium or green alga, but its affinities are unclear (Riding 1991a). We regard it as a Microproblematicum (Fig. 3).

Rothpletzella gotlandica (Rothpletz) Wood, 1948
(Fig. 9G)

1948 *Rothpletzella gotlandica* Rothpletz; Wood: 19, pl. 2, figs A, B.

1948 *Rothpletzella munthei* Rothpletz; Wood: 19, pl. 4, figs A, B.

1956 *Coactilum sraelenii* Maslov: 28, pl. 3, text-fig. 3.

Material. Present in reef limestone in the Yijianfang Formation (O_{2y}) of wells TK1 and HA902, reef limestone and oncolites in the Lianglitag Formation (O_{3l}) of wells TZ822, TZ826, TZ242, TZ30, TZ72, TZ58, TZ63, TZ82, TZ83, TZ161, M401 and M5, and in oncolites in the Sangtamu Formation (O_{3s}) of wells TZ35, LN46, YW2 and HE3.

Description. Filaments relatively short and fan-like in arrangement, ~0.5 mm in length, 30–35 µm in external diameter, increasing along branch.

Comparison. *Rothpletzella munthei* could be regarded as a junior synonym of *Rothpletzella gotlandica* since it only differs in size, and then only slightly; Wood (1948) suggested it might be a depauperate form growing under unfavourable conditions.

Rothpletzella longita sp. nov.
(Fig. 9H)

2011 *Rothpletzella* sp. Liu *et al.*: 496, pl. 3, fig. 2.

Material. Holotype: thin section from a depth of 5967.06 m in well TZ822, housed in the C-PCTOC; Upper Ordovician, Katian Stage (Lianglitag Formation); Tarim Basin, Xinjiang Province, Northwest China. Present in reef limestone and oncolites in the Lianglitag Formation (O₃l) of wells TZ822, TZ826, TZ242, TZ30, TZ72, TZ58, TZ63, TZ82, TZ83, TZ161, M401 and M5.

Diagnosis. Filaments very long and nearly parallel.

Description. Filaments sub-parallel and closely juxtaposed in longitudinal section (Fig. 9H), up to 10 mm long, external diameter ~65 µm; walls thin, 3–4 µm, micritic.

Remarks. The filaments of the new species are parallel and appear to be the longest reported for the genus: compare *R. gotlandica* (Wood 1948, p. 19, pl. 2, figs A, B, pl. 4, figs A, B), *R. exile* (Wray 1967, p. 39, pl. 9, figs 2, 5–7) and *R. magnum* (Wray 1967, p. 37, pl. 9, figs 3, 4).

Genus *Garwoodia* Wood, 1941

Type species. *Mitcheleania gregaria* Nicholson, 1888; Carboniferous; Scotland.

Diagnosis. Thallus sub-rounded or elongate, consisting of calcareous filaments radiating from the base. Locally, filaments branch at angles up to 90° and then turn parallel to the parent filament (Fig. 3).

Comparisons. Wood (1941) considered the taxon described as *Mitcheleania nicholsoni* by Wethered (1886) to be *Girvanella nicholsoni*, and assigned the specimen described as *Mitcheleania gregaria* by Nicholson (1888) to *Garwoodia gregaria*. These fossils resemble some of members of the *Hedstroemia* group, but can be distinguished by their branching pattern.

Affinity. Luchinina (in Chuvashov *et al.* 1987) regarded *Garwoodia* as a cyanobacterium, together with *Bija*, *Ortonella*, *Hedstroemia* and *Cayeuxia*. Riding (1991a) found it difficult to consider *Garwoodia* as a cyanobacterium due to its large tubes, and regarded it as Microproblematicum. Dragastan (1993) attributed *Garwoodia* to the green algae,

based on its relatively large tube diameter. Some of our Tarim specimens are smaller, 30 µm in diameter (Fig. 9J), than is usual for *G. gregaria*. We consider *Garwoodia* to be a Microproblematicum (Fig. 3).

Garwoodia gregaria Nicholson, 1888, emend.
Wood, 1941
(Fig. 9I, J)

1941 *Garwoodia gregaria* (Nicholson); Wood: 222, pl. 14, figs 1, 2.

1975 *Garwoodia gregaria* (Nicholson) Wood; Mamet & Roux: 151, pl. 8, figs 6, 8, 9.

1976 *Garwoodia gregaria* (Nicholson) Wood; Guilbault & Mamet: 642, pl. 2, figs 2, 3.

1990 *Garwoodia media* (Nicholson) Wood; Bian & Zhou: pl. 1, figs 7, 9.

Material. Present in the Lianglitag Formation (O₃l) of wells TZ23, TZ30, TZ35, TZ43, TZ16, TZ241, TZ161, TZ83, M5, M401 and HE3. The specimens mainly occur in micritic limestones.

Description. Thallus spherical or elongate, ~2 mm long; filaments relatively short, ~0.1–0.2 mm long (Fig. 9I, J), cross section rounded; diameter 30 µm (Fig. 9J) to 50 µm (Fig. 9I).

Garwoodia americana (Johnson) Liu & Riding,
comb. nov.
(Fig. 9K)

1961 *Cayeuxia americana* Johnson: 148, pl. 31, figs 3–5.

Material. Locally present in the Lianglitag Formation of wells TZ73, TZ58 and TZ161. The specimens mainly occur in skeletal packstone-grainstone.

Description. Thallus spherical, ~1.5 mm wide; filaments long, flexuous, closely packed, diameter ~30 µm.

Comparison. Johnson (1961) described the new species *Cayeuxia americana*, which Dragastan (1985) subsequently placed in *Mitcheleania* as *M. americana*. Based on Wood's (1941) opinion of *Mitcheleania* and *Garwoodia*, we assign *M. americana* to *Garwoodia*. The filaments of *Garwoodia americana* are significantly longer than those of *Garwoodia gregaria*.

Discussion

Diversity of the Tarim Ordovician flora

Previous work on the Tarim Ordovician calcified cyanobacteria and associated microfossils is quite limited (Riding & Fan 2001; Zhu *et al.* 2006; Wang *et al.* 2009, 2011; Rong *et al.* 2014; Zhang *et al.* 2014). Based on our

revision, these studies identify a flora of nine species belonging to nine genera: *Girvanella problematica*, *Subtiflora delicata*, *Renalcis granosus*, *Bevocastria conglobata*, *Rothpletzella gotlandica*, *Wetheredella silurica*, *Epiphyton* sp., *Ortonella furcata* and *Zonotrichites lissaviensis*. In a preliminary report of the current study (Liu *et al.* 2011), we recognized 13 genera of calcified cyanobacteria, including *Dimorphosiphonoides* and *Nuia*, which we now exclude from the cyanobacteria and their associated fossils. Our new results presented here confirm the presence of all these taxa and add several more, increasing the Tarim Ordovician assemblage of these fossils to at least 32 species belonging to 20 genera, as illustrated in Figure 3. Of these, 14 genera can confidently be regarded as cyanobacteria or probable cyanobacteria (*Girvanella*, *Subtiflora*, *Razumovskia*, *Acuasiphonoria* gen. nov., *Hedstroemia*, *Cayeuxia*, *Bija*, *Apophoretella*, *Ortonella*, *Zonotrichites*, *Bevocastria*, *Proaulopora*, *Phacelophyton* and *Gomphosiphon* gen. nov.) and 6 genera are of uncertain affinities (*Renalcis*, *Izhella*, *Epiphyton*, *Rothpletzella*, *Wetheredella* and *Garwoodia*).

Comparison with other Ordovician floras

Previous reports of Ordovician calcified cyanobacteria and microfossil floras have been concentrated in Europe, Siberia, North America, South America and China, with a few from South America as mentioned above. These occurrences are illustrated in Online Supplementary Material Table 2, and demonstrate that none of these floras contained more than eight genera and eight species, and overall totalled 13 genera. There are also 12 genera present in the Tarim flora, with exception of *Obruchevella spiralis* (Online Supplementary Material Table 2).

Compared with other Ordovician floras, we can see that amongst the 20 genera and 32 species (including three uncertain species) of the Tarim flora, 6 genera are recorded in the Ordovician for the first time: *Acuasiphonoria* gen. nov., *Gomphosiphon* gen. nov., *Izhella*, *Apophoretella*, *Cayeuxia* and *Bija*. Fourteen species are recorded in the Ordovician for the first time: *Acuasiphonoria ordovica* gen. et sp. nov., *Gomphosiphon xinjiangensis* gen. et sp. nov., *Izhella nubiformis*, *Apophoretella dobunorum*, *Cayeuxia moldavica*, *C. piae*, *Bija sibirica*, *Rothpletzella longita* sp. nov., *Proaulopora pachydermatica* sp. nov., ?*Girvanella* sp., *G. kasakiensis*, *Renalcis seriata*, *Ortonella tenuissima* and *Garwoodia americana*.

The Tarim assemblage reported here is considerably more diverse than other previously described Ordovician floras. It constitutes the most diverse calcified cyanobacterial flora hitherto known from the Ordovician, and represents a substantial addition to diversity, not only for the Tarim region but for the Ordovician worldwide. Calcified cyanobacteria and associated microfossils described from the Ordovician have generally been regarded as sparse, to

the point that the Middle and Late Ordovician was at one time considered as an episode of reduced cyanobacterial calcification (Riding 1991a, 1992). Our results prompt reconsideration of this view.

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Supplemental material

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