

1 Microbialite development through the Ediacaran–Cambrian transition in China:
2 Distribution, characteristics, and paleoceanographic implications

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20 **Abstract**

21 Widespread development of microbialites harbors a series of clues about microbial activity,
22 environmental condition, and aquatic chemistry. The Ediacaran-Cambrian transition draws
23 extensive attention on the co-evolution of complex life and Earth's environment but the
24 associated microorganism development has been largely ignored. In this study, we present a
25 high-resolution database with respect to the spatial and temporal distributions of microbialites
26 in China through the terminal Ediacaran to the early Cambrian Period and describe
27 morphological and petrological characteristics of stromatolites and thrombolites in detail to
28 shed light on the evolutionary process of microbial carbonates. Microbialite development
29 experienced two thriving intervals during the Ediacaran-Cambrian transition: latest Ediacaran
30 to early Fortunian, and Cambrian Age 3 to middle Age 4. The columnar and domical
31 stromatolites show no marked morphological changes in the Ediacaran-Cambrian transition,
32 but stratiform stromatolites exhibit a notable decline in Cambrian time, likely caused by
33 increasing bioturbation in the Cambrian shelf environments. Meanwhile, thrombolites evolved
34 to form large and complicated structures in the early Cambrian featured by meter-level mound
35 morphology and columnar-branching microbial forms (fan-like/dendritic structures), likely
36 indicating an improved environmental adaptation (e.g., photosynthesis efficiency and
37 hydrodynamic conditions). Another remarkable change in microbialites is the emergence of
38 large numbers of calcified microbial microfossils preserved within the laminated/clotted
39 mesostructures in Cambrian facies, compared with the Ediacaran forms that lack such unique
40 structural features. For the main control over the Cambrian microbial calcification event, this
41 study stresses again the essential role of seawater chemistry (Mg/Ca molar ratios and Ca^{2+}

42 concentrations) in the formation and preservation of calcified microorganisms based on
43 previous insights and elaborate characteristics of their occurrence and microstructures in China.

44 The transition of the Neoproterozoic “aragonite-dolomite sea” to the Cambrian “calcite sea”
45 (likely widely distributed in Age 3) may have promoted to the generation of an original calcite
46 mineralogy in microbial fossils, which has a stronger ability to resist diagenetic dissolution and
47 substitution (e.g., phosphatization and silicification) than that of the aragonite precursor.

48

49 **Keywords:** Stromatolites, thrombolites, microbial carbonates, cyanobacteria, calcified
50 microbes, calcite sea

51 **1. Introduction**

52 As one of the oldest sedimentary records related to biological activity on Earth,
53 microbialites **are a component** the evolution of the marine ecological system and seawater
54 chemical composition and thus have been broadly used to restore paleoceanographic and
55 paleoenvironmental information about the setting in which they formed (e.g., [Burne and Moore,](#)
56 [1987](#); [Grotzinger and Knoll, 1999](#); [Riding, 2000](#)). Microbialites, including stromatolites
57 (laminated structure), thrombolites (clotted structure), and other minor types, largely represent
58 a lithified benthic microbial community with the contribution of authigenic precipitation
59 (generally carbonate) during diagenesis, and sometimes with the admixtures of skeletal
60 organisms and terrigenous detritus ([Burne and Moore, 1987](#)). In terms of the formation
61 mechanism, both microbially-induced and microbially-influenced processes likely played key
62 roles in the mineralization of the microbial community, which contains a series of autotrophic
63 (e.g., cyanobacteria) and heterotrophic (e.g., sulfate reducing bacteria) microorganisms (e.g.,
64 [Visscher and Stolz, 2005](#); [Dupraz et al., 2009](#); [Riding, 2011b](#)).

65 Cyanobacteria are seen as one of the most important producers of carbonate precipitation
66 and organic matter, but their calcified microfossils are not ubiquitously preserved in rocks ([Arp](#)
67 [et al., 2001](#); [Planavsky et al., 2009](#)). The calcification of cyanobacteria refers to the sheath,
68 which is one form of extracellular polymeric substance (EPS) affiliated with (and close to)
69 microorganisms that has been internally crystallized by carbonate minerals, creating calcified
70 microbial microfossils ([Riding, 1977, 2011a](#)). Calcified cyanobacteria are rare in modern
71 marine environments, but they are present in several peaks in the geological record, e.g.,
72 Cambrian to Ordovician, Devonian to Carboniferous, and Late Triassic ([Arp et al., 2001](#)). There

73 is still controversy concerning the development of large-scale cyanobacterial calcification, but
74 its potential paleoceanographic and paleoenvironmental applications, e.g., seawater saturation
75 state, atmospheric CO₂ level, and dissolved oxygen state, are attracting increasing amounts of
76 attention (Knoll et al., 1993; Riding and Liang, 2005; Altermann et al., 2006; Kah and Riding,
77 2007; Riding et al., 2019).

78 The abundance of calcified cyanobacteria in Precambrian strata is very low when
79 compared to that in Phanerozoic strata (Golubic and Seong-Joo, 1999; Arp et al., 2001; Schopf,
80 2006; Schirrmeister et al., 2016). Although numerous studies have reported the presence of
81 microbial microfossils in Ediacaran records, most of the preservation types are post-mortem,
82 e.g., kerogenization, phosphatization, pyritization, and silicification or (partially) replacement
83 by Al-silicates during early diagenesis (Zhang et al., 1998; Brasier et al., 2011; Cai et al., 2012;
84 Muscente et al., 2015). The following Cambrian period is regarded to have been an intense
85 “cyanobacterial calcification episode” (Riding, 1992), which is represented by large quantities
86 of calcified microbes in space and time (Riding, 1982; 1992; Rowland and Shapiro, 2002; Lee
87 et al., 2015). Most of these sheath/wall calcified microbes are cyanobacteria (e.g., *Girvanella*
88 and *Botomaella* groups) and suspected cyanobacteria (*Epiphyton* and *Renalcis* groups) (Riding,
89 2001), but they are generalized as calcified microbial microfossils in this study due to their
90 similar preservation characteristics in microstructures and the ambiguous taxonomic
91 assignment in specific types (e.g., Pratt, 1984; Stephens and Sumner, 2002; Ibarra and Sanon,
92 2019). Previous studies have provided a variety of information on the petrological and
93 morphological characteristics of these calcified microbes (e.g., Rowland and Gangloff, 1988;
94 Knoll et al., 1993; Shapiro, 2000; Turner et al., 2000; Zhuravlev, 2001; Rowland and Shapiro,

95 2002), but little is known about the evolutionary process of calcified microbes during the
96 Ediacaran-Cambrian transition and about the similarities and differences of the characteristics
97 of microbialites formed in the latest Precambrian and earliest Phanerozoic.

98 High seawater Ca^{2+} concentrations or CaCO_3 supersaturation states are interpreted to have
99 driven the cyanobacterial calcification episodes, which provided sufficient Ca^{2+} for CaCO_3
100 nucleation on and within the sheath matrix (Arp et al., 2001; Riding and Liang, 2005). The
101 CO_2 -concentrating mechanisms (CCMs) likely played a role in the specific biologic processes
102 that form an alkaline gradient by transporting bicarbonate into the cell and releasing OH^- to the
103 sheaths during photosynthesis (Kaplan and Reinhold, 1999; Badger and Price, 2003; Riding,
104 2006). Even so, other potential effects, e.g., the Mg/Ca molar ratio, require systematic
105 assessment in this cyanobacterial calcification episode to understand its possible synergic
106 relationship with the seawater chemistry and environmental conditions. Seawater Mg/Ca molar
107 ratio dominates the carbonate mineralogical compositions, and the transition from the
108 aragonite-dolomite sea state in the Neoproterozoic to the calcite sea state in the early Cambrian
109 may have favored the preservation of original calcite microfossils due to the thermodynamic
110 differences between the primary carbonate minerals (Morse and Mackenzie, 1990; Brennan et
111 al., 2004; Zhuravlev and Wood, 2008; Hood et al., 2011; Wood et al., 2017). In addition,
112 cyanobacteria are one of the most important sources of atmospheric O_2 in Earth's early history
113 as a result of oxygen-producing photosynthesis, and they possibly played a key role in the
114 Proterozoic oxygenation event (Campbell and Allen, 2008; Lyons et al., 2014). The rise of
115 Eukaryotic algae evolved to more efficient phosphorus and organic carbon burial and
116 potentially increased ocean and atmospheric O_2 contents in the Neoproterozoic time (Lenton et

117 al., 2014; Lenton and Daines, 2018), but the roles of prokaryotes (e.g., cyanobacteria) have
118 generally been ignored in the environmental evolution at that time. A case from modern oceans
119 shows that the photosynthetic prokaryote *Prochlorococcus*, which is one species of
120 cyanobacteria and the most abundant photosynthetic organism on Earth, may contribute about
121 20% O₂ to the atmosphere (Partensky et al., 1999; Munn, 2020); it implies that photosynthetic
122 cyanobacteria are still of crucial value in O₂ production in the younger Earth. For these reasons,
123 photosynthesis-dominated microbial communities with calcified functional microstructures,
124 which were preserved in the laminated and clotted structures of microbialites during the early
125 Cambrian, seem to provide vital atmospheric O₂ information about this time period, and this
126 assumption needs to be clarified.

127 The aims of this study are to recover the evolution of microbialites during the transition
128 from the Ediacaran to the Cambrian and to understand the paleoceanographic and
129 paleoenvironmental significance of their morphological and functional changes during this
130 crucial period. For this purpose, first we built a database (n = 212) on the development of
131 microbialites from the uppermost Ediacaran to Cambrian Series 2 in China. Then, we
132 generalized the exterior (growth forms) and interior (laminated/clotted structures)
133 characteristics of the microbialites in different temporal intervals and focused on the occurrence,
134 distribution, and microstructures of the calcified microbes in the early Cambrian. Next, we
135 assessed the potential significance of the microbialite response to environmental changes in the
136 early Cambrian. Finally, we attempted to interpret the startup mechanism of the Cambrian
137 cyanobacterial calcification event from a paleoceanographic perspective.

138

139 2. Geologic background

140 Paleogeographically, there are three major blocks in China: the South China, Tarim, and
141 North China blocks. These blocks were located at low latitudes (approximately between 30°N
142 and 30°S) adjacent to Gondwana during the transition from the Ediacaran to the Cambrian (Fig.
143 1A and B) (Torsvik et al., 2013). The time interval of this study ranges from the latest Ediacaran
144 (informal Age 6) to the end of the early Cambrian (informal Age 4) according to the newly
145 published reference stratigraphic framework in China, which approximately corresponds to
146 550 to 509 Ma (Fig. 1C) (Zhou et al., 2019; Zhu et al., 2019). The South China and Tarim
147 blocks experienced similar shallow-water depositional successions in the upper Ediacaran and
148 lower Cambrian, but the North China Block contains a large unconformity between the upper
149 Tonian (Neoproterozoic) and the Cambrian Terreneuvian (hiatus of 150–300 Ma) (He et al.,
150 2017). Until Cambrian Epoch 2, the transgressive sediments gradually overlay the large
151 unconformity in the North China Block (Meng et al., 1997).

152

153 2.1 South China Block

154 The South China Block consisted of two collided blocks (the Yangtze and Cathaysia blocks)
155 during the Ediacaran-Cambrian transition (Fig. 1A) (Zhang et al., 2013). The Yangtze Block
156 was covered by carbonate-dominated sedimentation in the latest Ediacaran and principally
157 exhibited extensive microbial carbonate factories characterized by massive stromatolites and
158 thrombolites in space and time (Ding et al., 2019; Zhai et al., 2020). The Yangtze shelf was
159 exposed above sea level to varying degrees during the global regression near the Ediacaran–
160 Cambrian boundary (Shahkarami et al., 2020), which led to an extensive hiatus between the

161 upper Ediacaran and lower Cambrian strata. Some areas that were located within intracratonic
162 rifts (e.g., northern Yunnan) or in a slope setting (e.g., Hunan and eastern Guizhou) on the
163 Yangtze Block preserve relatively complete successions from the uppermost Ediacaran to
164 Cambrian Terreneuvian, and they are characterized by phosphorites, phosphorous siltstones,
165 calcareous-siliceous phosphorites, and a few phosphate stromatolites (Chen and Chen, 1987;
166 Mu and Wu, 2005; Sun et al., 2020a).

167 The following transgression from Age 2 to Age 3 flooded most of the Yangtze shelf and
168 developed broad fine-grained, organic-rich siliciclastic deposits that likely extended to the early
169 Age 3 (Mei et al., 2007; Mou et al., 2012; Peng et al., 2020). Subsequently, clastic and mixed
170 carbonate-siliciclastic sedimentation was preserved in several of the near-shore environments
171 adjacent to the massifs in the northern and western parts of the Yangtze Block during the middle
172 to late parts of Age 3 (Mou et al., 2012; Liu et al., 2015; Zeng et al., 2020). This depositional
173 sequence was episodically intercalated by a carbonate-dominant depositional succession
174 characterized by oolites, microbialites, and microbial-archaeocyathan limestones deposited in
175 high-energy shoals and microbial mound/reef environments on the western Yangtze shelf
176 (Hicks and Rowland, 2009; Yang and Yuan, 2012; Zhang et al., 2017b; Tang et al., 2019). With
177 the gradual aggradation/progradation developed in the interior of the Yangtze Block from Age
178 3 to Age 4, the western Yangtze area formed a system of lagoons and restricted platforms (Li
179 and He, 2014). Meanwhile, the middle (the Three Gorges area) and southeastern (Guizhou and
180 Hunan areas) parts of the Yangtze Block gradually developed shallow-water ooid shoals and
181 microbial reefs/mounds on the rims of the shelf (Zhang and Yuan, 1994; Li and He, 2014).
182 During the late Age 4, the rimmed margins of the northeastern and southeastern parts of the

183 Yangtze shelf extended to northern Hubei, western Hunan and eastern Guizhou, respectively
184 (Mou et al., 2012; Zheng, 2016). In addition, the available studies on the eastern Yangtze area
185 are insufficient, and some studies show the development of stromatolites in the shallow subtidal
186 settings in Epoch 2 (e.g., Zhang and Sun, 1991).

187

188 2.2 Tarim Block

189 The upper Ediacaran and lower Cambrian shallow-water depositional successions are well
190 exposed in northwestern Tarim (Keping area) and are partially present in southwestern Tarim
191 (Tiekelike area). During the latest Ediacaran, the Tarim Block was split into two depositional
192 basins along an east-west massif (Shi et al., 2016). In the Keping area, the Ediacaran
193 microbialites developed mainly in tidal flat and inner ramp settings of the Chigebrak Formation,
194 which roughly corresponds to the Dengying Formation in the South China Block based on
195 biostratigraphic and C and Sr isotope chemostratigraphic evidence (Gao, 1990; Zhang et al.,
196 2020). The Yurtus Formation that covers the upper part of the Chigebrak Formation is
197 characterized by calcareous-siliceous phosphorites, phosphorous siltstones, and thinly bedded
198 siliciclastic rocks (small shelly fossil (SSF) zone, *Anabarites-Protoherzina* Zone, Fortunian
199 Stage), while its upper part consists of alternating dolomite and siltstone successions and
200 nodular dolomite (SSF, *Lapworthella-Ninella-Cambroclavus* assemblages, lower Stage 3) (Fig.
201 1C) (Zhou, 2001; Zhu et al., 2019). Stromatolites are **not very** common in the Yurtus Formation
202 (Gao et al., 1987). The depositional sequences of the Xiaoerbrak Formation overl**ie** the Yurtus
203 Formation and likely correspond to Stage 3 in light of the positive C isotope variation that is similar
204 to the MICE (Mingxinsi carbon isotopic excursion) and the *Shizhudiscus*, *Ushbaspis*, and

205 *Kepingaspis-Tianshanocephalus* trilobite zones (Fig. 1C) (Zhou, 2001; Zhang et al., 2020). The
206 Xiaerbrak Formation consists of thickly bedded microcrystalline dolomites with large-scale
207 microbialite mound/reef structures in its upper part. It is overlain by the Wusonger Formation,
208 which is characterized by medium to thinly bedded, finely crystalline dolomite (trilobite
209 *Paokannia* Zone, lower part) (Fig. 1C) (Zhou, 2001; Zhang et al., 2017a). The basal Shayilik
210 Formation overlying the Wusonger Formation exhibits a significant negative C isotope
211 excursion ($\delta^{13}\text{C}_{\text{minimum}} = -13\text{‰}$, VPDB) (Zhang et al., 2020), which is consistent with the
212 ROECE (*Redlichiid-Olenellid* extinction C-isotope excursion) between Series 2 and the
213 Miaolingian, evidence that the Wusonger Formation ranges from the uppermost part of Stage 3
214 to Stage 4 (Zhu et al., 2019).

215 In the Tiekelike area, upper Ediacaran microbialites are developed in members II and IV
216 of the Kezisuhumu Formation, which exhibit depositional successions similar to those in the
217 Chigebrak Formation of the Aksu area (Peng and Gao, 1984). In addition, large amounts of
218 glacial diamictites (Hankalchough Formation) developed in eastern Tarim during the late
219 Ediacaran (Gao et al., 1980). Although some stromatolite breccias appear near the top of the
220 glacial diamictites in the Hankalchough Formation in northwestern Tarim, the source of the
221 breccias is uncertain and has been inferred from the underlying Shuiquan Formation (Gao et
222 al., 1980). Since the sedimentary age of the Shuiquan Formation remains controversial
223 (possibly middle Ediacaran) (Xiao et al., 2004; Xu et al., 2009; Zhou et al., 2019; Xiao and
224 Narbonne, 2020), the microbialite record in the Hankalchough Formation was not incorporated
225 into this study.

226

227 2.3 North China Block

228 Available studies indicate that the development of uppermost Ediacaran strata in the North
229 China Block is rare and no microbialite records have been reported in this interval although the
230 uncertainty remains (Wan et al., 2019; Zhou et al., 2019). The initial transgressive
231 sedimentation was diachronous in the different areas of the North China Block during the early
232 Cambrian, which shows that the earliest sediments were composed of phosphorite, phosphorite
233 breccia, and phosphorous siltstone and carbonate with the emergence of diagnostic fossils in
234 the upper part of Stage 3 to the lower part of Stage 4 in the northeastern (Shuidong Formation,
235 Jilin) (Yue et al., 1990), western (basal Suyukou Formation, Ningxia; trilobite *Estaingia*
236 (*Hsuaspis*) Zone) (Regional Stratigraphic Chart Writing Group, 1980), southwestern (lower
237 Xinji Formation, Shaanxi; SSF *Stenotheca drepanoida*–*Pelagiella madianensis* Zone; trilobite
238 *Estaingia* (*Hsuaspis*) Zone) (Yun et al., 2016), and southeastern (lower Houjiashan Formation;
239 trilobite *Estaingia* (*Hsuaspis*) Zone) margins of the North China Block (Fig. 1C) (Zhang and
240 Zhu, 1979; Miao, 2014; Wan et al., 2019). Since the diachronicity generally occurs in the
241 lithostratigraphic units of the lower Cambrian in the North China Block, the initial deposition
242 within the interior of the North China Block was generally younger than in its marginal settings
243 (Meng et al., 1997).

244 A continuous transgression caused extensive near-shore siliciclastic and mixed
245 siliciclastic-carbonate successions on the North China Block, with numerous shallow-water
246 ooid and microbial deposits in the scattered shoal settings in Age 4 (generally corresponding to
247 the trilobite *Palaeolenus* (*Megapalaeolenus*) *fengyangensis*, *Redlichia chinensis*, and *R. nobilis*
248 zones in ascending order) (Fig. 1C) (Lee et al., 2018). Microbialite records have been reported

249 in tidal flat and inner ramp successions (lower to middle part of Stage 4), including in the
250 Heigou, Jianchang, Cangping, Zhushadong, Houjiashan (upper member), and Xinji (upper
251 member) formations (Hong et al., 1991; Lee and Chough, 2011; Chang et al., 2013; Miao, 2014;
252 Du et al., 2019). The microbialite in the overlying Mantou Formation (member I, upper Stage
253 4) exhibits a much wider spatial distribution in the interior of the North China Platform than
254 the older Cambrian successions (e.g., Lee and Chough, 2011; Chang et al., 2013). These
255 microbialites (member I of the Mantou Formation) developed in mixed siliciclastic-carbonate
256 systems, generally in tidal flats, and they are underlain by the widespread transgressive
257 sequences (shales and mudstones; trilobite *Yaojiayuella* Zone) that generally overlies the lower
258 Cambrian strata in the North China Block (Wu et al., 2018).

259

260 **3. Materials and methods**

261 3.1 Microbialite development database

262 We compiled a microbialite development database (MDD), which systematically catalogs
263 the microbialite development sites and other relative information, including ages,
264 lithostratigraphic units, locations, and morphological characteristics from the latest Ediacaran
265 to Cambrian Age 4 in China (~550 to 509 Ma) (Table S1). The sources of the MDD includes
266 our visited field outcrops, peer-reviewed papers, books, doctoral and master's theses, and
267 regional geological reports (scale 1:200 000 and others), which were mostly written in Chinese.
268 The lithostratigraphic units of all of the sites have been corrected to the latest
269 chronostratigraphic framework for the upper Ediacaran and lower Cambrian in China (Zhou et
270 al., 2019; Zhu et al., 2019). Some of the microbialite sites lack available biostratigraphic and/or

271 chemostratigraphic evidence, and thus, their corresponding development ages mainly rely on
272 neighboring well-studied sections (Table S1).

273

274 3.2 Description of the microbialites

275 For the description of the characteristics of the microbialite in the Ediacaran-Cambrian
276 transition, we follow the terminologies of Shapiro (2000) and Riding and Voronova (1985) for
277 the external morphology and the internal fabric and microbial groups, respectively. The
278 macrostructure (meter level) and mesostructure (cm level) characteristics of the microbialites
279 rely on field observation and on polished slabs (n = 42). In addition, microstructure
280 examinations were conducted on thin-sections (n >400) using a polarizing microscope (Leica
281 DM2700P) at Southwest Petroleum University. One-half of each thin-section was stained with
282 Alizarine Red S to distinguish the carbonate mineralogical compositions (calcite vs. dolomite).
283 For purposes of comparison, we counted the width and the longest diameter of the *Epiphyton*
284 in the microscopic photos, which were acquired from the thin-sections of Cambrian Stages 3
285 and 4 (n = 419 and 601, respectively). It should be noted that all the measured values are
286 reported as mean \pm 1 σ , unless otherwise indicated.

287

288 4. Results

289 4.1 Spatial and temporal distributions of microbialite records in the Ediacaran–Cambrian 290 transition

291 Detailed information on the microbialite development was tabulated in the MDD (Table
292 S1), and corresponding specific sites were plotted on the paleogeographic maps (uppermost

293 Ediacaran and lower Cambrian) of China using their latitude-longitude coordinates (Figs. 2 and
294 3). Based on the MDD, the development of microbialites in China during the Ediacaran–
295 Cambrian transition can be subdivided into two intervals: Ediacaran Age 6 to Cambrian
296 Fortunian, and Cambrian Age 3 to middle Age 4 (Table S1). The South China and Tarim blocks
297 experienced two periods of microbialite development, but the North China Block contains only
298 the interval from the lower to middle Stage 4 (Figs. 2 and 3). Both stromatolites and
299 thrombolites developed in the latest Ediacaran and Cambrian Age 3 to 4, but only stromatolites
300 appear in the Cambrian Fortunian based on the available data (Table S1).

301 The stromatolites are widely distributed in the Yangtze shelf and occupy a predominant
302 position in the uppermost Ediacaran in the middle and eastern areas. The thrombolites are
303 generally associated with stromatolites in the shallow-water depositional successions of the
304 western Yangtze shelf, while they formed composite laminated and clotted framework
305 structures (Fig. 2 and Table S1). The situation of the development of the microbialites in Tarim
306 is similar to that of the western Yangtze shelf. The following flourishing of stromatolites
307 appeared in the Aksu area of the Tarim Block and in the southwestern South China Block during
308 the Cambrian Fortunian (Fig. 3). The earliest Cambrian thrombolite dominant microbial
309 bioherms are located in the northwestern South China Block and are preserved within the lower
310 to middle Stage 3 strata. Subsequently, the thrombolite and stromatolite records spread to the
311 Aksu area of the Tarim Block and the Guizhou area of the South China Block in upper Stage 3
312 depositional successions (Fig. 3). The broadest distribution of the microbialite beds in the lower
313 Cambrian occurs in the lower and middle parts of Stage 4, which show a gradual eastward
314 expansion on the Yangtze shelf, and a seaward expansion in the Tarim Block (Fig. 3). In the

315 North China Block, the earliest appearance of microbialites in the Cambrian strata was likely
316 in early Age 4, and according to the available MDD, they were mainly distributed in temporal
317 proximity in the northeastern, western, southwestern, and southeastern edges of the block
318 (Table S1). Subsequently, the distribution of the microbialite successions underwent a stepwise
319 expansion from the near-shore settings on the edges of the North China Block to the interior
320 during Age 4 (Fig. 3).

321

322 4.2 Macrostructure and mesostructure of microbialites and their sedimentary characteristics

323 Based on the MDD and the examination (field and slab) of the microbialites in the
324 Ediacaran–Cambrian transition (Figs. 4–7), the stromatolites can be divided into three major
325 categories: (1) columnar or domical in shape, a general height of <0.3 m, and close-packed with
326 a roughly uniform thickness (Figs. 4A–B, 6A, and 7A); (2) a regular linear structure, alternating
327 dark and light layers, and a thickness generally ranging from tens of centimeters to one meter
328 (Figs. 4C, 5A, 6B, and 7B); and (3) a low- or high-relief laminated fabric coupled with a
329 convex-upward characteristic (Figs. 4D and E, and 6C). For the thrombolites, they are present
330 as (1) narrow-laminar or patchy structures (with thickness <0.1 m), generally developed
331 between the stromatolitic layers in the upper Ediacaran (Figs. 4F, 5B–C); (2) a thinly bedded
332 tabular fabric (~1 to 10 cm) with large numbers of tens of millimeter clots, and alternating
333 laminated and clotted structures (Figs. 4G, 5D, and 7C); (3) low- or high-relief mounds (one to
334 tens of meters in width) composed of plentiful clotted textures ranging from millimeters to
335 centimeters in size, partially with the participation of the macro-organisms (e.g., archaeocyath)
336 (Figs. 6D–E, and 7D–G); and (4) meter-level frameworks with a variety of columnar branching

337 structures (e.g., fine and thick branches; Figs. 6F–G, and 7H).

338

339 4.3 Mineralogical and petrological characteristics of the stromatolites and thrombolites

340 Mineralogical compositions of the microbialites investigated in this study are different. In
341 the uppermost Ediacaran, nearly all the stromatolites and thrombolites have been dolomitized
342 (unstained) but most of their fine structures were retained (Fig. 8). The dark-colored laminae in
343 the stromatolites are cryptocrystalline and consist of plentiful very fine dolomite crystals
344 (generally <2 μm); and the neighboring light-colored layers are composed of medium- to fine-
345 grained dolomite grains (4–40 μm) and a few dolospar crystals (Fig. 8A). For the Ediacaran
346 thrombolites, the clotted structures are also composed of cryptocrystalline dolomites, and their
347 early-stage cements are generally composed of isopachous, fibrous to acicular dolomite grains
348 (Fig. 8B–D). Yet, in the late-stage, the pore-filling cements are either medium- to coarse-
349 grained dolomite (Fig. 8B–G) or coarsely crystalline calcite grains (Fig. 8H).

350 Unlike the uniform dolomitization (uppermost Ediacaran; Fig. 8) and phosphatization
351 (Cambrian Terreneuvian) (Fig. 9A), microbialites in Cambrian Stages 3 and 4 exhibit
352 mineralogical and preservation characteristics that differ in the three blocks (Figs. 9B–H and
353 10). The stromatolites and thrombolites generally exhibit well-formed calcified microbial
354 microfossils in Stage 3 and lower Stage 4 (Figs. 9B–G, and 10A and C), but they exhibit poorly-
355 preserved laminated/clotted structures in upper Stage 4 (Fig. 10D and E), with preservation
356 characteristics resembling those of contemporaneous carbonate ooids (Fig. 10A, B, D, and F).
357 In Tarim, the primary microbial fabrics and intergranular spaces in the microbialites have been
358 replaced by fine and medium to coarsely crystalline dolomite grains, respectively (Fig. 9H).

359

360 4.4 Calcified microbes within the stromatolites and thrombolites

361 The parallel and wavy laminae (generally with thickness of <1 mm) of the stromatolites
362 show dark-colored, dense, microcrystalline fabrics in the uppermost Ediacaran; and loose
363 peloids, lamination fragments, and aggregate grains are common in the interlaminar layers of
364 the stromatolites (Fig. 8A). The contemporaneous thrombolites exhibit irregular clotted
365 structures, which are composed of cryptocrystalline aggregate grains and/or hollow peloidal
366 clusters (Fig. 8B–H). Mineralized globular and botryoidal fabrics are common in the microbial
367 carbonates, but no visible calcified microbes were identified under the microscope in the
368 uppermost Ediacaran specimens from a series of sections from the Tarim and South China
369 blocks (Fig. 8).

370 In contrast, the stromatolites and thrombolites in Cambrian Stages 3–4 exhibit large
371 numbers of calcified branched, chambered, and tubiform microfossils (Fig. 9B–G). In Stage 3,
372 plentiful *Epiphyton* and *Renalcis* microbes form the clotted structures of the thrombolites, with
373 minor contributions from *Tarthinia*, *Girvanella*, and other groups (Fig. 9B–D). The *Epiphyton*-
374 dominant microbes can also form erect structures that show dendritic (thick) and fan-like (or
375 bushy; thin) branches in the field (Fig. 6F and G). The *Girvanella*-group is common in the
376 laminated structures of stromatolite in Stage 3, but other calcified groups are rare (Fig. 9B). In
377 Stage 4, tubiform microbes (e.g., *Botomaella* and *Hedstroemia*) and *Epiphyton* became the
378 dominant microfossils in the microbialites (Fig. 9E–G). Among these microbial groups,
379 tubiform microbes were identified both in the laminated and clotted structures, and their
380 microstructures are characterized by large numbers of branched and overlapping tubes (Figs.

381 [6H](#), [7C](#), and [9 F](#)). The *Epiphyton* microbes are still the major constructor of the clot structures
382 of the thrombolites and their widths ($73\pm 37\ \mu\text{m}$, $n = 305$) and the lengths ($208\pm 118\ \mu\text{m}$, $n =$
383 296) were uniformly larger in Stage 4 than in Stage 3 (width: $48\pm 11\ \mu\text{m}$, $n = 297$; length:
384 144 ± 67 , $n = 122$).

385

386 **5. Discussion**

387 5.1 Co-evolution of microbialite development and environmental conditions during the
388 Ediacaran-Cambrian transition

389 5.1.1 Comparison of the characteristics of microbialites between the uppermost Ediacaran and
390 lower Cambrian

391 The uppermost Ediacaran and lower Cambrian microbialites have some structural
392 similarities. Decimeter-scale, domical and columnar stromatolite types are common in the
393 uppermost Ediacaran, Cambrian Fortunian, and Stage 4 strata, and no substantial changes in
394 morphology and laminated structure occurred during the Ediacaran-Cambrian transition ([Figs.](#)
395 [4A and B](#), [6A and B](#), [7A](#), and [9B](#); [Table S1](#)). These stromatolites may have developed in a
396 shallow subtidal setting resembling that of modern stromatolites in the Hamelin Pool, Australia
397 ([Jahnert and Collins, 2011, 2012](#)). These small-scale stromatolites have been regarded as being
398 formed in the intervals of the highstand systems following the transgressive sequences, e.g., the
399 lower Chigebrek Formation ([Fig. 4A and B](#); Ediacaran Stage 6), the basal Yurtus ([Fig. 7A](#)) and
400 Meishucun formations (Cambrian Fortunian) ([Sun et al., 2020b](#)), and the lower Zhushadong
401 Formation (Cambrian Stage 4) ([Chang et al., 2012](#)). The **shape** and size of the thrombolitic clots
402 in the uppermost Ediacaran strata of the Tarim and western Yangtze shelf ([Fig. 8B–H](#)) also

403 resemble their descendants in Cambrian Stages 3–4 (Fig. 9C, D, and F–H), which exhibit well
404 cemented, millimeter-scale granular aggregates. Especially for some of the thrombolitic clots
405 composed of **microcrystalline** dolomite (Fig. 9H) or cryptocrystalline (Fig. 10E) structures in
406 the Cambrian, their characteristics are very similar to those in the uppermost Ediacaran (Fig.
407 **8E–H**). In addition, the features of the thrombolitic clots in the uppermost Ediacaran in China
408 are comparable to those in other blocks (Turner et al., 2000; Harwood and Sumner, 2011; 2012;
409 Adachi et al., 2019), implying that their morphological compositions were relatively stable in
410 the Neoproterozoic.

411 The thickly bedded stratiform stromatolites experienced a marked decline during the
412 Ediacaran-Cambrian transition. It is common to find thickly bedded, meter-scale stratiform
413 stromatolites with nearly parallel millimeter-scale laminae in the Tarim and Yangtze shelf in the
414 uppermost Ediacaran strata (Figs. 4C and 5A). Based on their well-preserved, smoothly
415 laminated features, their depositional environment appears to have been situated on the open
416 shelf, generally between the deep subtidal and storm wave base settings (Fig. 11A). However,
417 the distribution of the thickly bedded stratiform stromatolites significantly decreased in the
418 lower Cambrian strata in China based on the MDD and our field observations (Table S1). Only
419 a few stratiform stromatolites have been identified in relatively restricted environments in Stage
420 4, which is evidenced by extensive dolomitization and the rare appearance of skeletal fossils
421 (Fig. 6B). The stratiform stromatolites were replaced with strongly bioturbated carbonates
422 characterized by micritic, irregularly-distributed burrows and mottled structures (also called
423 leopard rock in China) in the shelf environments (Fig. 11B). The latter shows an increasing
424 trend in the early Cambrian in the North and South China blocks (e.g., Zhang et al., 1981; Qi

425 et al., 2014; Yang et al., 2016; Han et al., 2017; Chen et al., 2019). The relationship between
426 the decline of the stratiform stromatolites and the increase of metazoan activities in terms of
427 their spatial distributions allows for the assumption that the evolved animals had much
428 enhanced capabilities to burrow into and out of the microbial mats in Cambrian Epoch 2
429 compared with the latest Ediacaran (e.g., Xiao et al., 2019), which is consistent with our
430 understanding of seafloor burrowing activity at that time (Fig. 11B) (Seilacher and Pflüger,
431 1994; Bottjer et al., 2000).

432 Thrombolites evolved to form complicated structures in the Cambrian. Morphologically,
433 Ediacaran thrombolites generally exhibit patchy and medium to thinly bedded (thickness of a
434 single layer generally <0.5 m) clotted textures (solid and/or hollow), and commonly co-exist
435 with the stromatolites in terms of their depositional successions (Fig. 4F–H). The Cambrian
436 thrombolites exhibit mound-like shapes and were much larger than those in the upper Ediacaran
437 (meter-scale), and they developed individual and calcimicrobial–archaeocyath bioherms in the
438 shallow-water settings in China (e.g., Fig. 6D) (Adachi et al., 2013; Tang et al., 2019), which
439 is similar to the synthesized ranges of their depositional distribution in other blocks (James and
440 Gravestock, 1990; Zhuravlev and Wood, 1995; Rowland and Shapiro, 2002; Gandin and
441 Debrenne, 2010). Structurally, some new erect, columnar-branching forms are present in the
442 lower Cambrian thrombolites, which are characterized by fan-like (thin branches) and dendritic
443 (thick branches) structures (Figs. 6F–G, and 7H). These erect mesostructures show marked
444 differences from the common ellipsoid-like clotted textures in both the terminal Ediacaran and
445 the early Cambrian, likely indicating an adaptive response to different hydrodynamic conditions,
446 and to the expanded contact area with seawater for the release of O₂ via photosynthesis (Riding,

447 2006). Another important change in the thrombolites (and stromatolites) was the emergence of
448 calcified microbial microfossils in their microstructures in the early Cambrian (See Section 5.2).

449

450 5.1.2 The relationship between large-scale microbialite development and atmospheric O₂ level

451 Distributions and characteristics of the microbialites may provide a new perspective on the
452 development of prokaryotes during the Ediacaran-Cambrian transition. The atmospheric and
453 oceanic O₂ contents in the Neoproterozoic and early Paleozoic had a significant impact on the
454 early evolution of eukaryotes, and thus, have received a great deal of attention (e.g., Holland,
455 2006; Planavsky et al., 2021). The atmospheric O₂ content experienced a marked increase (from
456 roughly 1% to 100% of the present atmospheric O₂ level) in the late Neoproterozoic (Lenton et
457 al., 2014; Lyons et al., 2014; Reinhard and Planavsky, 2020); and the surface oceans are
458 interpreted to have been in an oxic state, which may have facilitated the evolution of life forms
459 despite the fact that the deep oceans remained anoxic (Wood et al., 2019). During this period,
460 the rise of complex eukaryotes might facilitate the burial of more organic carbon and
461 phosphorus and indirectly elevate the oceanic O₂ level (Lenton et al., 2014; Lenton and Daines,
462 2018). Direct assessment of the contemporaneous prokaryotic development is quite difficult;
463 the microbialite, as a major sedimentary carrier of prokaryotic communities and activities, may
464 provide a window to understand their evolutionary processes in the Ediacaran-Cambrian
465 transition.

466 The large-scale microbialite development may have been related to oxygenated periods in
467 the surface oceans. Although the principal source of O₂ in early Earth history remains
468 controversial (volcanic degassing versus oxygenic photosynthesis) (Kopp et al., 2005; Kump

469 and Barley, 2007; Campbell and Allen, 2008; Gaillard et al., 2011; Ward et al., 2016), the O₂
470 produced by oxygenic photosynthesis in shallow marine environments can be seen as an
471 essential O₂ source for sustaining the oxic surface oceans and buffering the anoxic waters of
472 the deeper oceans (Fig. 11). As the major source of atmospheric O₂ in modern oceans (Partensky
473 et al., 1999; Munn, 2020), photosynthetic cyanobacteria may also play an essential role in
474 regulating the O₂ production in the Ediacaran-Cambrian transition due to their vast quantities
475 of biomass. The microbialite development shows two thriving intervals during the Ediacaran-
476 Cambrian transition, i.e., in the latest Ediacaran to early Fortunian (stratiform stromatolite
477 dominant; ca. 550 to 538 Ma), and in Cambrian Age 3 to middle Age 4 (branching thrombolite
478 dominant; ca. 518 to 512 Ma), which is roughly consistent with the higher rates of net
479 atmospheric O₂ production and primary production in the global oceans at that time (Fig. 12)
480 (Wei et al., 2021). Thrombolites and stromatolites appeared in considerable quantities in
481 settings from shallow-water shelf to onshore environments in China (this study) and other
482 continents (Riding and Voronova, 1984; Bechstädt et al., 1988; Rowland and Gangloff, 1988;
483 James and Gravestock, 1990; Wood et al., 1993; Zhuravlev, 1996; Feldmann and McKenzie,
484 1998; Rowland and Shapiro, 2002; Javier Alvaro et al., 2006; Creveling et al., 2013; Cordie et
485 al., 2019), and they could produce adequate O₂ and facilitate the oxygenation of the surface
486 oceans during the Ediacaran-Cambrian transition.

487

488 5.2 The start of the Cambrian cyanobacterial calcification event in China

489 5.2.1 Spatial and temporal distributions of calcified microfossils in the lower Cambrian
490 microbialites

491 The Cambrian cyanobacterial calcification event began in early Age 3 in China. Available
492 data show that the earliest appearance of credible calcified microbes was in the early Age 3
493 (Yang, 2005; Hicks and Rowland, 2009; Zhang et al., 2017b; Tang et al., 2019), which
494 corresponds to the strata of the lower Xiannüdong Formation in the northwestern part of the
495 South China Block (northern Sichuan and southern Shaanxi) based on biostratigraphic
496 (archaeocyathan zonations of *Dailycyathus xiuqiensis* and *Dictyocyathus shaanxiensis*) and
497 carbon isotope chemostratigraphic (initial stage of the MICE) evidence (Fig. 1) (Yang et al.,
498 2016; Zhu et al., 2019). Microbialites bearing calcified microfossils generally developed in the
499 near-shore settings around the Hannan-Micangshan massif at that time (Zeng et al., 2020); and
500 the major microbial groups included *Epiphyton*, *Renalcis*, *Tarthinia*, and *Girvanella* (Fig. 9B–
501 D). All of these calcified microorganisms can contribute to the formation of the clotted
502 structures of thrombolites (Fig. 7D–G), but only the *Girvanella*-group was visible in the
503 laminated fabrics of the stromatolites observed in this study (Fig. 9B).

504 The following interval from late Age 3 to middle Age 4 shows a peak of extensive
505 occurrence of calcified microbes. In the South China Block, a lot of calcified microbe-bearing
506 microbialites develop in Guizhou in the strata of upper Stage 3 based on the biostratigraphic
507 data (archaeocyathan zonation of *Sibirecyathus meitanensis*; Fig. 1 and Table S1) (Mei et al.,
508 2007; Yang et al., 2016). Moreover, the *Epiphyton* group (Song et al., 2014) and possibly
509 *Tarthinia* (Fig. 9H) were present within the thrombolites in the Aksu area of Tarim based on the
510 diagnostic C isotope curve (MICE) and the trilobite zone (*Kepingaspis*–*Tianshanocephalus*)
511 (Fig. 1) (Zhou, 2001; Zhang et al., 2020). The association of calcified microbial microfossils
512 and minor archaeocyaths widely reappeared in the South China Block after the Archaeocyathid

513 Extinction Carbon isotope Excursion (AECE; archaeocyathan *Archaeocyathus yanjiaoensis*
514 beds/ trilobite *Palaeolenus fengyangensis* Zone) (Figs. 1 and 3) (Zhang and Yuan, 1994; Yang,
515 2005; Mei et al., 2007; Adachi et al., 2013; Yang et al., 2016). After the archaeocyathan
516 extinction, individual microbial reefs/mounds developed on the rims of the eastern Yangtze
517 shelf in the middle of Age 4 (*Hoffetella*–*R. murakamii* and *R. guizhouensis* trilobite zones) (Fig.
518 3), which consists of plentiful microfossils formed by *Epiphyton*, *Botomaella* and other
519 tubiform microbes (Figs. 7C and H, and 9E–G). The microbialites in the North China Block
520 also recorded the emergence of the *Girvanella* group (Zhang et al., 1981; Mei et al., 2019) and
521 *Epiphyton* and tubiform microbes (Lee et al., 2014), which is roughly consistent with the timing
522 of those in the South China Block during Age 4 (corresponding to *Palaeolenus fengyangensis*,
523 *R. chinensis*, and *R. nobilis* trilobite zones) (Figs. 1 and 3, and Table S1) (Zhang and Liu, 1996;
524 Bureau of Geology and Mineral Resources of Jilin Province, 1997).

525

526 5.2.2 Comparison of the start of the Cambrian cyanobacterial calcification event on a global
527 scale

528 The initiation of the Cambrian cyanobacterial calcification event likely occurred in the
529 Fortunian. After examining the occurrence of calcified microfossils in the lower Cambrian
530 strata in different blocks, it was determined that the Siberia platform has one of the earliest
531 records of calcified microbes (*Renalcis* and *Korilophyton* microbes dominate) with widely-
532 distributed stromatolitic structures (limestones) in the upper Nemakit-Daldynian Stage (*Purella*
533 *antiqua* Zone) (Khomentovsky and Karlova, 1993; Luchinina et al., 1997; Luchinina et al.,
534 2013), which can be assigned to the upper Fortunian based on the latest international

535 chronostratigraphic framework (Peng et al., 2020). Similar calcified microbial microfossils are
536 also preserved in contemporaneous Mongolia (Kruse et al., 1996). Adachi et al. (2021) recorded
537 a much earlier occurrence of calcified microbial microfossils than that of the previous study in
538 Mongolia, which is ~50 m higher than the Ediacaran-Cambrian boundary (according to the
539 Basal Cambrian Carbon isotope Excursion) in height. The distribution of calcified microbes
540 shows a wider range in Age 2, including in Australia (Betts et al., 2016), Mongolia (Riding and
541 Voronova, 1985), Siberia (Riding and Voronova, 1985; Riding and Zhuravlev, 1995; Luchinina
542 and Terleev, 2008), and Morocco (Latham and Riding, 1990); and they began to be associated
543 with archaeocyaths (Riding and Zhuravlev, 1995). Both the major groups of microbial
544 microfossils and the structures of the microbial mounds/reefs in Stages 3–4 exhibit high
545 similarities in China (Figs. 6, 7, and 9) and other contemporaneous regions (Wood et al., 1993;
546 Zhuravlev, 1996; Riding, 2001; Rowland and Shapiro, 2002). A questionable earliest
547 appearance of calcified microbes (*Girvanella*-rich layer; thickness of ~10 cm) (Zhang and Sun,
548 1991) has been classified in the strata of the Fortunian Stage in the eastern Yangtze shelf based
549 on C isotope chemostratigraphic data (Li et al., 2017), but currently, the biostratigraphic
550 evidence is insufficient and controversial (Zhang and Sun, 1991; Qian, 1999; Xue and Zhou,
551 2006). If the chemostratigraphic correlation in this region is correct, the first occurrence of
552 calcified microbes in the South China Block may be consistent with those in Siberia and
553 Mongolia (Fig. 12). Since the three major blocks in China had latitudinal ranges similar to those
554 of the abovementioned blocks from the Fortunian to Age 2, the lack of coeval calcified microbes
555 (based on microscopically petrological evidence) may be related to the limited shallow-water
556 carbonate records and further investigations may fill in this distribution gap.

557

558 5.2.3 The eve of the Cambrian cyanobacterial calcification event: a prelude or nothing?

559 The exceptional preservation of non-calcified cyanobacteria from the Ediacaran to the
560 earliest Cambrian cannot be seen as the beginning of the cyanobacterial calcification event. A
561 series of sites containing cyanobacterial groups have been identified in the lower Fortunian in
562 the South China and Tarim blocks; however, nearly all of these microfossils are preserved
563 within the phosphorites/cherts and their well-formed microstructures are generally
564 permineralized by apatite and/or quartz (Qian et al., 2007; Cui et al., 2020). These two main
565 mineralization processes are generally regarded as very early phosphate/silicate replacements
566 that occurred before the dead microorganisms decayed in a shallow burial environment, and
567 such mechanisms are also documented in the fossil preservation in the Ediacaran (Zhang et al.,
568 1998; Muscente et al., 2015; Anderson et al., 2017). Evidence from scanning electron
569 microscope photomicrographs also supports the presence of apatite- or quartz-replaced
570 microstructures on the walls of the microbial microfossils (Cui et al., 2020) based on the criteria
571 for judging the primary and secondary microstructures (Brasier, 1990).

572 Characteristics of the microbialites indicate a low possibility that the cyanobacterial
573 calcification event began in the Ediacaran. Large numbers of stromatolite and thrombolite
574 records are developed in the uppermost Ediacaran strata in the South China and Tarim blocks,
575 but nearly no reliable calcified cyanobacteria could be identified in this study and previous
576 studies have rarely mentioned their occurrence. Instead, the lithification of microbial mats is
577 common in the uppermost Ediacaran microbialites in China, which occur as numerous dense,
578 mineralized laminated and clotted fabrics (Fig. 8). Most of the microbial mineralization fabrics

579 in the South China and Tarim blocks is regarded as evidence that post-mortem mineralization
580 of degraded microbial communities during early diagenesis (Dupraz et al., 2009). Similar
581 mineralization characteristics of laminated and clotted structures also developed in early to late
582 Neoproterozoic microbialites (e.g., Turner et al., 2000; Harwood and Sumner, 2011; 2012;
583 Adachi et al., 2019). It is not clear which type(s) of microorganisms played the key role in the
584 mat lithification due to the currently limited evidence, but the lack of *in vivo* cyanobacterial
585 calcification appears to indicate that in the latest Ediacaran the cyanobacteria had a limited
586 mineralization ability, which may have affected their efficiency at fixing carbon and producing
587 O₂ during diurnal cycles (Dupraz et al., 2009). One possible reason for this is that the long-term
588 low atmospheric CO₂ concentrations in the Neoproterozoic slowed down the development of
589 CCMs (Riding, 2011a). Since the sheath-calcified cyanobacteria have a longer history than the
590 Neoproterozoic (since the Mesoproterozoic) (Kah and Riding, 2007), the deficiency of the
591 broad occurrence of calcified cyanobacteria preserved in the upper Ediacaran is evidence that
592 the start of the cyanobacterial calcification event was no earlier than the earliest Cambrian.

593

594 5.3 Paleooceanographic conditions for initiation of the Cambrian cyanobacterial calcification
595 event

596 5.3.1 The primary mineralogical composition of calcified microbes in Cambrian Age 3

597 The well-formed, calcified microbial microfossils in Cambrian Stage 3 indicate a primary
598 calcite mineralogy. There are three major original mineralogical types, i.e., aragonite, low-Mg
599 calcite, and high-Mg (>4 mol% MgCO₃) calcite, for the compositions of skeletal and non-
600 skeletal carbonates. Calcified cyanobacteria have these three mineralogies in nature (Plée et al.,

601 2008; Planavsky et al., 2009; Pace et al., 2018), but the preservation of the original aragonite
602 mineralogy in ancient sediments is rather difficult because aragonite has a weak thermodynamic
603 stability and is easily recrystallized and transformed into stable low-Mg calcite (Morse et al.,
604 2007). The high-Mg calcite crystals with <8.5 mol% MgCO₃ are more stable than aragonite
605 (Berner, 1975); they can preserve a weakly altered morphology in relatively-closed systems
606 when compared to aragonite (James and Kobluk, 1978; Sandberg, 1983; Wilkinson and Owen,
607 1985; Richter et al., 2011). There are three commonly-used criteria for judging original
608 carbonate mineralogies, including (1) the degree of preservation of the primary microstructure,
609 (2) the crystallographic features and secondary inclusions (e.g., microdolomite), and (3) the
610 major element composition (e.g., Sr contents indicating aragonite or calcite; Mg contents
611 indicating high or low Mg calcite) (James and Kobluk, 1978; Sandberg, 1983; Wilkinson and
612 Owen, 1985). The microbial microfossils in Stage 3 generally exhibit well-formed
613 cryptocrystalline microstructures and have very low concentrations of Mg and Sr in their walls
614 (2.4 mol% MgCO₃ and ~350 ppm Sr) (Gong et al., 2021). The associated ooid grains exhibit
615 subtle concentric-radial cortical fabrics and have also low Mg and Sr contents (3 mol% MgCO₃
616 and ~385 ppm Sr) (Gong et al., 2021), which indicate a primary low-Mg calcite mineralogy
617 (Fig. 10A and B, arrowed). In addition, very few calcified microfossils show the occurrence of
618 microdolomite inclusions although their petrological features are similar to normal forms (Fig.
619 10C), possibly implying a high-Mg primary mineralogical composition. Microbial microfossils
620 in the lower part of Stage 4 have similar petrological and major element compositions (0.7 mol%
621 MgCO₃ and 245 ppm Sr, unpublished data), which are significantly different from the
622 petrological features of the oolites and microbialites in the upper part of Stage 4 (Fig. 10D-F).

623

624 5.3.2 A paleoceanographic model of the start of the Cambrian cyanobacterial calcification event

625 Although the markedly elevated Ca concentrations of the seawater and the enhanced
626 CCMs may have facilitated the extensive calcification in the early Cambrian (Arp et al., 2001;
627 Riding, 2006), whether these microfossils can be readily preserved in rocks depends mainly on
628 their primary carbonate mineralogies. Here, we propose an updated model of the rapid and
629 extensive emergence and preservation of calcified microbes in early Cambrian (Fig. 12). The
630 secular evolution of the Mg/Ca molar ratio of seawater played a key role during the early
631 Cambrian, but this has not been unanimously accepted (Sandberg, 1983; Hardie, 1996). Some
632 recent insights suggest that the turnover from an aragonite-dolomite sea to a calcite sea in terms
633 of seawater compositions began in Age 3 based on halite fluid inclusions and non-skeletal
634 carbonate mineralogies (oids and cements) (Lowenstein et al., 2001; Brennan et al., 2004;
635 Petrychenko et al., 2005; Porter, 2007; Zhuravlev and Wood, 2008). It is assumed that the
636 capability of cyanobacteria to mediate the mineralogical composition of their calcified sheaths
637 is much weaker than that of the skeletal organisms (Ries et al., 2008; Ries, 2010). The
638 microbially induced mineralization appears not to change the aqueous Mg/Ca molar ratios of
639 microdominants, which means that the Mg/Ca molar ratio of seawater was probably the major
640 factor controlling their mineralogical compositions (Ries et al., 2008; Ries, 2010).

641 The primary low-Mg calcite mineralogy of calcified microfossils generally has the optimal
642 microstructures; and microbial microfossils with a high-Mg calcite precursor (>4 mol% and
643 <8.5 mol% MgCO₃) are likely to exhibit medium to good preservation. Calcified microfossils
644 with original aragonite mineralogy are easily dissolved and recrystallized during diagenesis,

645 making their primary characteristics (e.g., walls and tubes) hard to identify. The low- and high-
646 Mg calcite mineralogies of microbial microfossils are beneficial to the preservation of their
647 primary morphologies in spite of the fact that the latter may suffer stronger diagenetic alteration
648 than the former. Since the high- and low-Mg non-skeletal carbonates develop under >1 and <1
649 Mg/Ca molar ratio conditions (or 2–5.3 and <2 Mg/Ca molar ratio conditions), respectively
650 (Hardie, 1996; Stanley, 2008), the significant decline in the Mg/Ca ratio of the seawater from
651 the late Ediacaran to the early Cambrian seems to be responsible for the extensive preservation
652 of calcimicrobes (Fig. 12). It is concluded that the combination of elevated Ca concentrations
653 and enhanced CCMs (for the occurrence of calcified microbes), as well as the calcite sea
654 condition (for their preservation) facilitated the start of the calcification event in the early
655 Cambrian.

656

657 6. Conclusions

658 Based on our high-resolution database and systematic petrological examination of
659 microbialites in the three major blocks in China from the terminal Ediacaran to the early
660 Cambrian, we drew the following conclusions:

661 (1) The Ediacaran-Cambrian transition was marked by the widespread distribution of
662 microbialites in China, and two thriving intervals in the latest Ediacaran to early Fortunian
663 and the Cambrian Age 3 to middle Age 4. The development of columnar and domical
664 stromatolites (inferred from shallow subtidal settings) does not appear to have been affected
665 during the transition, but the presence of stratiform stromatolites composed of nearly
666 parallel laminae (inferred from open shelf) significantly decreased in the Cambrian, which

667 was associated with increasingly bioturbated structures in the seafloor sediments.
668 Thrombolites evolved to form large and complicated structures in the Cambrian when
669 compared to those in the Ediacaran, including mound-like shapes and **branching** forms (fan-
670 like/dendritic textures).

671 (2) There were no visible changes in the **shape** of the laminae/clots within the microbialites
672 during the Ediacaran-Cambrian transition. Calcified microbial microfossils are common
673 within the stromatolites and thrombolites of Cambrian Series 2, but they are not seen in the
674 mineralized laminated/clotted microstructures in the upper Ediacaran. The types and
675 characteristics of the calcified microbial microfossils conform well to those of other blocks
676 during the Cambrian cyanobacterial calcification event. This calcification event likely
677 began in the Fortunian, and the petrological and sedimentological evidence from the
678 microbialite microstructures formed in the Precambrian-Cambrian transition do not support
679 an earlier beginning in the Ediacaran.

680 (3) Except for the active CO₂-concentrating mechanisms and the increase in the Ca²⁺ content of
681 the seawater (**for the occurrence of calcified microbes**), the primary calcite mineralogical
682 composition of the microbial microstructures is one potential reason for the preservation of
683 microfossils in the microbialites **during early Cambrian time**. Our model **predicts** that the
684 transition from the Neoproterozoic aragonite-dolomite sea to the Cambrian calcite sea
685 promoted formation of an original calcite mineralogy in microbial fossils, which has a
686 stronger ability to resist diagenetic alteration than that of the aragonite precursor.

687

688 **Acknowledgments**

689 This study was supported by the NSFC (grant numbers 41872119 and 41502115) and the

690 Science and Technology Planning Project of Sichuan Province (grant number 20YYJC1185).

691 We thank Zhengtang Guo (editor-in-chief) and Zhong-Qiang Chen (guest editor) for editorial

692 handling and two anonymous reviewers for their thoughtful comments.

693

694 **References**

695

- 696 Adachi, N., Nakai, T., Ezaki, Y., Liu, J. (2013) Late Early Cambrian archaeocyath reefs in
697 Hubei Province, South China: modes of construction during their period of demise.
698 *Facies* 60, 703-717.
- 699 Adachi, N., Ezaki, Y., Liu, J., Watabe, M., Sonoda, H., Altanshagai, G., Enkhbaatar, B.,
700 Dorjnamjaa, D. (2019) Late Ediacaran *Boxonia*-bearing stromatolites from the Gobi-
701 Altay, western Mongolia. *Precambrian Research* 334, 105470.
- 702 Adachi, N., Ezaki, Y., Liu, J., Watabe, M., Altanshagai, G., Enkhbaatar, B., Dorjnamjaa, D.
703 (2021) Earliest known Cambrian calcimicrobial reefs occur in the Gobi-Altai, western
704 Mongolia: Intriguing geobiological products immediately after the Ediacaran–
705 Cambrian boundary. *Global and Planetary Change* 203, 103530.
- 706 Altermann, W., Kazmierczak, J., Oren, A., Wright, D. (2006) Cyanobacterial calcification and
707 its rock - building potential during 3.5 billion years of Earth history. *Geobiology* 4,
708 147-166.
- 709 Anderson, R.P., Macdonald, F.A., Jones, D.S., McMahon, S., Briggs, D.E.G. (2017)
710 Doushantuo-type microfossils from latest Ediacaran phosphorites of northern
711 Mongolia. *Geology* 45, 1079-1082.
- 712 Arp, G., Reimer, A., Reitner, J. (2001) Photosynthesis-induced biofilm calcification and
713 calcium concentrations in Phanerozoic oceans. *Science* 292, 1701-1704.
- 714 Badger, M.R., Price, G.D. (2003) CO₂ concentrating mechanisms in cyanobacteria: molecular
715 components, their diversity and evolution. *Journal of experimental botany* 54, 609-
716 622.
- 717 Bechstädt, T., Schledding, T., Selg, M. (1988) Rise and fall of an isolated, unstable carbonate
718 platform: The Cambrian of Southwestern Sardinia. *Geologische Rundschau* 77, 389-
719 416.
- 720 Berner, R.A. (1975) The role of magnesium in the crystal growth of calcite and aragonite
721 from sea water. *Geochim. Cosmochim. Acta* 39, 489-504.
- 722 Betts, M.J., Paterson, J.R., Jago, J.B., Jacquet, S.M., Skovsted, C.B., Topper, T.P., Brock,
723 G.A. (2016) A new lower Cambrian shelly fossil biostratigraphy for South Australia.
724 *Gondwana Res.* 36, 176-208.
- 725 Bottjer, D.J., Hagadorn, J.W., Dornbos, S.Q. (2000) The Cambrian substrate revolution. *GSA*
726 *today* 10, 1-7.
- 727 Brasier, M.D. (1990) Phosphogenic events and skeletal preservation across the Precambrian-
728 Cambrian boundary interval. Geological Society, London, Special Publications 52,
729 289-303.
- 730 Brasier, M.D., Antcliffé, J.B., Callow, R.H.T., (2011) Evolutionary trends in remarkable fossil
731 preservation across the Ediacaran–Cambrian transition and the impact of metazoan
732 mixing, In: Allison, P.A., Bottjer, D.J. (Eds.), *Taphonomy: Process and Bias Through*
733 *Time*. Springer Netherlands, Dordrecht, pp. 519-567.
- 734 Brennan, S.T., Lowenstein, T.K., Horita, J. (2004) Seawater chemistry and the advent of
735 biocalcification. *Geology* 32, 473.

736 Bureau of Geology and Mineral Resources of Jilin Province, 1997, Regional Geology of Jilin
737 Province. Geological Publishing House, Beijing.

738 Burne, R.V., Moore, L.S. (1987) Microbialites-organosedimentary deposits of benthic
739 microbial communities. *Palaios* 2, 241-254.

740 Cai, Y., Schiffbauer, J.D., Hua, H., Xiao, S. (2012) Preservational modes in the Ediacaran
741 Gaojiashan Lagerstätte: Pyritization, aluminosilicification, and carbonaceous
742 compression. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 326-328, 109-117.

743 Campbell, I.H., Allen, C.M. (2008) Formation of supercontinents linked to increases in
744 atmospheric oxygen. *Nature Geoscience* 1, 554-558.

745 Chang, Y., Qi, Y., Zheng, W., Sun, F. (2012) Assemblages and controlling factors of the
746 Cambrian stromatolites in Dengying, Henan Province. *Acta Micropalaeontologica*
747 *Sinica* 29, 341-351.

748 Chang, Y., Huang, H., Zheng, W., Sun, F. (2013) Sedimentary characteristics of microbialites
749 of the North China type in Mantou Formation of Cambrian, Henan. *Journal of China*
750 *University of Mining & Technology* 42, 236-242.

751 Chen, Z.-Q., Tu, C., Pei, Y., Ogg, J., Fang, Y., Wu, S., Feng, X., Huang, Y., Guo, Z., Yang, H.
752 (2019) Biosedimentological features of major microbe-metazoan transitions (MMTs)
753 from Precambrian to Cenozoic. *Earth-Science Reviews* 189, 21-50.

754 Chen, Z., Chen, Q. (1987) Paleogeography of Yangzi Platform and the characteristics of the
755 phosphorite distribution of early Meishucun Stage, Early Cambrian. *Scientia*
756 *Geologica Sinica* 22, 246-257.

757 Cordie, D.R., Dornbos, S.Q., Marengo, P.J., Oji, T., Gonchigdorj, S. (2019) Depauperate
758 skeletonized reef-dwelling fauna of the early Cambrian: Insights from archaeocyathan
759 reef ecosystems of western Mongolia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 514,
760 206-221.

761 Creveling, J.R., Fernández-Remolar, D., Rodríguez-Martínez, M., Menéndez, S., Bergmann,
762 K.D., Gill, B.C., Abelson, J., Amils, R., Ehlmann, B.L., García-Bellido, D.C.,
763 Grotzinger, J.P., Hallmann, C., Stack, K.M., Knoll, A.H. (2013) Geobiology of a
764 lower Cambrian carbonate platform, Pedroche Formation, Ossa Morena Zone, Spain.
765 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 386, 459-478.

766 Cui, L., Liu, W., Zhang, X. (2020) Phosphatized microbial fossils from the lowest Cambrian
767 of South China and their ecological and environmental implications for the
768 Kuanchuanpu biota. *Precambrian Research* 338, 105560.

769 Ding, Y., Chen, D., Zhou, X., Guo, C., Huang, T., Zhang, G. (2019) Tectono-depositional
770 pattern and evolution of the middle Yangtze Platform (South China) during the late
771 Ediacaran. *Precambrian Research* 333, 105426.

772 Du, S., Zhang, H., Gao, L., Fan, Y., Chen, J., Liu, F., Chen, C., Yang, A. (2019) Sequence
773 stratigraphic subdivision and evolution of depositional environment of Cambrian at
774 Zhangxia-Gushan area, Changqing County, Shandong Province. *Journal of*
775 *Stratigraphy* 43, 279-294.

776 Dupraz, C., Reid, R.P., Braissant, O., Decho, A.W., Norman, R.S., Visscher, P.T. (2009)
777 Processes of carbonate precipitation in modern microbial mats. *Earth-Science*
778 *Reviews* 96, 141-162.

779 Feldmann, M., McKenzie, J.A. (1998) Stromatolite-thrombolite associations in a modern
780 environment, Lee Stocking Island, Bahamas. *Palaios* 13, 201-212 English.

781 Gaillard, F., Scaillet, B., Arndt, N.T. (2011) Atmospheric oxygenation caused by a change in
782 volcanic degassing pressure. *Nature* 478, 229-232.

783 Gandin, A., Debrenne, F. (2010) Distribution of the archaeocyath-calcimicrobial
784 bioconstructions on the Early Cambrian shelves. *Palaeoworld* 19, 222-241.

785 Gao, Z., Peng, C., Li, Y., Jianxin, Q., Zhu, C., (1980) The Sinian system and its glacial
786 deposits in Quruqtagh, Xijiang, In: Wang, Y. (Ed.), *Research on Precambrian*
787 *Geology: Sinian Suberathem in China*. Tianjing Science and Technology Press,
788 Tianjing, pp. 186-213.

789 Gao, Z., Wang, W., Peng, C., Li, Y., Xiao, B., 1987, *The Sinian System on Aksu-Wushi*
790 *Region, Xinjiang, China*. Xijiang People's Publishing House, Urumchi.

791 Gao, Z. (1990) Characteristics of the sedimentary facies of the Upper Sinian Series in
792 Kezisuhumu section in southwestern margin of Tarim Basin. *Journal of Jiangnan*
793 *Petroleum Institute* 12, 9-19.

794 Golubic, S., Seong-Joo, L. (1999) Early cyanobacterial fossil record: preservation,
795 palaeoenvironments and identification. *European Journal of Phycology* 34, 339-348.

796 Gong, Q., Li, F., Lu, C., Wang, H., Tang, H. (2021) Tracing seawater- and terrestrial-sourced
797 REE signatures in detritally contaminated, diagenetically altered carbonate rocks.
798 *Chemical Geology* 570, 120169.

799 Grotzinger, J.P., Knoll, A.H. (1999) Stromatolites in Precambrian carbonates: evolutionary
800 mileposts or environmental dipsticks? *Annual Review of Earth and Planetary*
801 *Sciences* 27, 313-358.

802 Han, B., Feng, J., He, Z., Tian, H., Zhu, S., Wang, X. (2017) Origin of the Lower Cambrian
803 leopard-pattern limestones and its influence on reservoirs in the Sichuan Basin. *Oil &*
804 *Gas Geology* 38, 764-775.

805 Hardie, L.A. (1996) Secular variation in seawater chemistry: An explanation for the coupled
806 secular variation in the mineralogies of marine limestones and potash evaporites over
807 the past 600 m.y. *Geology* 24, 279-283.

808 Harwood, C.L., Sumner, D.Y. (2011) Microbialites of the Neoproterozoic Beck Spring
809 Dolomite, Southern California. *Sedimentology* 58, 1648-1673.

810 Harwood, C.L., Sumner, D.Y. (2012) Origins of microbial microstructures in the
811 Neoproterozoic Beck Spring Dolomite: Variations in microbial community and
812 timing of lithification. *Journal of Sedimentary Research* 82, 709-722.

813 He, T., Zhou, Y., Vermeesch, P., Rittner, M., Miao, L., Zhu, M., Carter, A., Pogge von
814 Strandmann, P.A.E., Shields, G.A. (2017) Measuring the 'Great Unconformity' on the
815 North China Craton using new detrital zircon age data. *Geological Society, London,*
816 *Special Publications* 448, 145-159.

817 Hicks, M., Rowland, S.M. (2009) Early Cambrian microbial reefs, archaeocyathan inter-reef
818 communities, and associated facies of the Yangtze Platform. *Palaeogeogr.*
819 *Palaeoclimatol. Palaeoecol.* 281, 137-153.

820 Holland, H.D. (2006) The oxygenation of the atmosphere and oceans. *Philos Trans R Soc*
821 *Lond B Biol Sci* 361, 903-915.

822 Hong, Z., Huang, Z., Liu, X., 1991, Upper Precambrian Geology in Southern Liaodong
823 Peninsula. Geological Publishing Press, Beijing.

824 Hood, A.v.S., Wallace, M.W., Drysdale, R.N. (2011) Neoproterozoic aragonite-dolomite seas?
825 Widespread marine dolomite precipitation in Cryogenian reef complexes. *Geology*
826 39, 871-874.

827 Ibarra, Y., Sanon, S. (2019) A freshwater analog for the production of Epiphyton-like
828 microfossils. *Geobiology* 17, 510-522.

829 Jahnert, R.J., Collins, L.B. (2011) Significance of subtidal microbial deposits in Shark Bay,
830 Australia. *Marine Geology* 286, 106-111.

831 Jahnert, R.J., Collins, L.B. (2012) Characteristics, distribution and morphogenesis of subtidal
832 microbial systems in Shark Bay, Australia. *Marine Geology* 303-306, 115-136.

833 James, N.P., Kobluk, D.R. (1978) Lower Cambrian patch reefs and associated sediments:
834 southern Labrador, Canada. *Sedimentology* 25, 1-35.

835 James, N.P., Gravestock, D.I. (1990) Lower Cambrian shelf and shelf margin buildups,
836 Flinders Ranges, South Australia. *Sedimentology* 37, 455-480.

837 Javier Alvaro, J., Clausen, S., Albani, A.E., Chellai, E.H. (2006) Facies distribution of the
838 Lower Cambrian cryptic microbial and epibenthic archaeocyathan-microbial
839 communities, western Anti-Atlas, Morocco. *Sedimentology* 53, 35-53.

840 Kah, L.C., Riding, R. (2007) Mesoproterozoic carbon dioxide levels inferred from calcified
841 cyanobacteria. *Geology* 35, 799-802.

842 Kaplan, A., Reinhold, L. (1999) CO₂ concentrating mechanisms in photosynthetic
843 microorganisms. *Annual Review of Plant Physiology and Plant Molecular Biology*
844 50, 539-570.

845 Khomentovsky, V.V., Karlova, G.A. (1993) Biostratigraphy of the Vendian-Cambrian beds
846 and the lower Cambrian boundary in Siberia. *Geological Magazine* 130, 29-45.

847 Knoll, A.H., Fairchild, I.J., Swett, K. (1993) Calcified microbes in Neoproterozoic
848 carbonates; implications for our understanding of the Proterozoic/Cambrian
849 transition. *Palaios* 8, 512-525.

850 Kopp, R.E., Kirschvink, J.L., Hilburn, I.A., Nash, C.Z. (2005) The Paleoproterozoic snowball
851 Earth: a climate disaster triggered by the evolution of oxygenic photosynthesis. *Proc.*
852 *Natl. Acad. Sci. USA* 102, 11131-11136.

853 Kruse, P.D., Gandin, A., Debrenne, F., Wood, R. (1996) Early Cambrian bioconstructions in
854 the Zavkhan Basin of western Mongolia. *Geological Magazine* 133, 429-444.

855 Kump, L.R., Barley, M.E. (2007) Increased subaerial volcanism and the rise of atmospheric
856 oxygen 2.5 billion years ago. *Nature* 448, 1033-1036.

857 Latham, A., Riding, R. (1990) Fossil evidence for the location of the Precambrian/Cambrian
858 boundary in Morocco. *Nature* 344, 752-754.

859 Lee, H.S., Chough, S.K. (2011) Depositional processes of the Zhushadong and Mantou
860 formations (Early to Middle Cambrian), Shandong Province, China: Roles of
861 archipelago and mixed carbonate-siliciclastic sedimentation on cycle genesis during
862 initial flooding of the North China Platform. *Sedimentology* 58, 1530-1572.

863 Lee, H.S., Chen, J., Han, Z., Chough, S.K. (2018) Depositional processes and environmental
864 changes during initial flooding of an epeiric platform: Ligan Formation (Cambrian
865 Series 2), Shandong Province, China. *Geosciences Journal* 22, 903-919.

- 866 Lee, J.-H., Chen, J., Chough, S.K. (2015) The middle-late Cambrian reef transition and
867 related geological events: A review and new view. *Earth-Science Reviews* 145, 66-84.
- 868 Lee, J.H., Lee, H.S., Chen, J., Woo, J., Chough, S.K. (2014) Calcified microbial reefs in
869 Cambrian Series 2, North China Platform: Implications for the evolution of Cambrian
870 calcified microbes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 403, 30-42 English.
- 871 Lenton, T.M., Boyle, R.A., Poulton, S.W., Shields-Zhou, G.A., Butterfield, N.J. (2014) Co-
872 evolution of eukaryotes and ocean oxygenation in the Neoproterozoic era. *Nature*
873 *Geoscience* 7, 257-265.
- 874 Lenton, T.M., Daines, S.J. (2018) The effects of marine eukaryote evolution on phosphorus,
875 carbon and oxygen cycling across the Proterozoic-Phanerozoic transition. *Emerg Top*
876 *Life Sci* 2, 267-278.
- 877 Li, J., He, D. (2014) Palaeogeography and tectonic-depositional environment evolution of the
878 Cambrian in Sichuan Basin and adjacent areas. *J Palaeogeog* 16, 441-460.
- 879 Li, W.-P., Zheng, Y.-F., Zhao, Y.-Y. (2017) Geochemical evidence from marine carbonate for
880 enhanced terrigenous input into seawater during the Ediacaran-Cambrian transition in
881 South China. *Precambrian Research* 291, 83-97.
- 882 Liu, J., Li, W., Zhang, B., Zhou, H., Yuan, X., Shan, X., Zhang, J., Deng, S., Gu, Z., Fan, R.,
883 Wang, Y., Li, X. (2015) Sedimentary palaeogeography of the Sinian in upper Yangtze
884 Region. *Journal of Palaeogeography* 17, 735-753.
- 885 Lowenstein, T.K., Timofeeff, M.N., Brennan, S.T., Hardie, L.A., Demicco, R.V. (2001)
886 Oscillations in Phanerozoic seawater chemistry: evidence from fluid inclusions.
887 *Science* 294, 1086-1088.
- 888 Luchinina, V., Korovnikov, I., Sipin, D., Fedoseev, A. (1997) Biostratigraphy of the Upper
889 Vendian-Lower Cambrian in the Sukharikha River section (Siberian platform).
890 *Geologiya i Geofizika* 38, 1346-1358.
- 891 Luchinina, V.A., Terleev, A.A. (2008) The morphology of the genus *Epiphyton* Bornemann.
892 *Geologia Croatica* 61, 105-111.
- 893 Luchinina, V.A., Korovnikov, I.V., Novozhilova, N.V., Tokarev, D.A. (2013) Benthic
894 Cambrian biofacies of the Siberian Platform (hyoliths, small shelly fossils,
895 archeocyaths, trilobites and calcareous algae). *Stratigraphy and Geological*
896 *Correlation* 21, 131-149.
- 897 Lyons, T.W., Reinhard, C.T., Planavsky, N.J. (2014) The rise of oxygen in Earth's early ocean
898 and atmosphere. *Nature* 506, 307-315.
- 899 Mei, M., Ma, Y., Zhang, H., Meng, X., Chen, Y. (2007) Sequence-stratigraphic frameworks
900 for the Cambrian of the Upper-Yangtze region: Ponder on the sequence stratigraphic
901 background of the Cambrian biological diversity events. *Journal of Stratigraphy* 31,
902 68-78.
- 903 Mei, M., Riaz, M., Liu, L., Meng, Q. (2019) Oncoids built by photosynthetic biofilms: An
904 example from the Series 2 of Cambrian at Fuzhouwan section in Liaotung Peninsula.
905 *J Palaeogeog* 21, 31-48.
- 906 Meng, X., Ge, M., Tucker, M.E. (1997) Sequence sequence stratigraphy, sea-level changes
907 and depositional systems in the Cambro-Ordovician of the North China carbonate
908 platform. *Sedimentary Geology* 114, 189-222.

909 Miao, L., (2014) Biostratigraphy of the Basal Cambrian Xinji Formation and the Houjiashan
910 Formation from the Southern North China Plate. The University of Chinese Academy
911 of Sciences/Nanjing Institute of Geology and Palaeontology, CAS, Nanjing, p. 127.
912 Morse, J.W., Mackenzie, F.T., 1990, *Geochemistry of Sedimentary Carbonates*. Elsevier,
913 Amsterdam.

914 Morse, J.W., Arvidson, R.S., Lüttge, A. (2007) Calcium carbonate formation and dissolution.
915 *Chemical Reviews* 107, 342-381.

916 Mou, C., Liang, W., Zhou, K., Ge, X., Kang, J., Chen, X. (2012) Sedimentary facies and
917 palaeogeography of the middle-upper Yangtze area during the Early Cambrian
918 (Terreneuvian-Series 2). *Sedimentary Geology and Tethyan Geology* 32, 41-53.

919 Mu, N., Wu, C. (2005) Characteristics and phosphogenesis of phosphorite of the Sinian-
920 Cambrian, West Yangtze Area. *Acta Scientiarum Naturalium Universitatis Pekinensis*
921 41, 551-562.

922 Munn, C.B., 2020, *Marine Microbiology: Ecology & Applications* (3rd Edition). CRC Press,
923 Boca Raton.

924 Muscente, A.D., Hawkins, A.D., Xiao, S. (2015) Fossil preservation through phosphatization
925 and silicification in the Ediacaran Doushantuo Formation (South China): a
926 comparative synthesis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 434, 46-62.

927 Pace, A., Bourillot, R., Bouton, A., Vennin, E., Braissant, O., Dupraz, C., Duteil, T.,
928 Bundeleva, I., Patrier, P., Galaup, S., Yokoyama, Y., Franceschi, M., Virgone, A.,
929 Visscher, P.T. (2018) Formation of stromatolite lamina at the interface of oxygenic-
930 anoxygenic photosynthesis. *Geobiology* 16, 378-398.

931 Partensky, F., Hess, W.R., Vaultot, D. (1999) *Prochlorococcus*, a marine photosynthetic
932 prokaryote of global significance. *Microbiol Mol Biol Rev* 63, 106-127 eng.

933 Peng, C., Gao, Z. (1984) Microflora and stromatolites from the late Precambrian on the
934 northern slope of W. Kunlun Mountains and their stratigraphic significance. *Xinjiang*
935 *Geology* 2, 17-28.

936 Peng, S., Babcock, L.E., Ahlberg, P., (2020) The Cambrian Period, In: Gradstein, F.M., Ogg,
937 J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *Geologic Time Scale 2020*. Elsevier, Boston,
938 pp. 565-629.

939 Petrychenko, O.Y., Peryt, T.M., Chechel, E.I. (2005) Early Cambrian seawater chemistry from
940 fluid inclusions in halite from Siberian evaporites. *Chemical Geology* 219, 149-161.

941 Planavsky, N., Reid, R.P., Lyons, T.W., Myshrall, K.L., Visscher, P.T. (2009) Formation and
942 diagenesis of modern marine calcified cyanobacteria. *Geobiology* 7, 566-576.

943 Planavsky, N.J., Crowe, S.A., Fakhraee, M., Beaty, B., Reinhard, C.T., Mills, B.J.W.,
944 Holstege, C., Konhauser, K.O. (2021) Evolution of the structure and impact of Earth's
945 biosphere. *Nature Reviews Earth & Environment*, <https://doi.org/10.1038/s43017-43020-00116-w>.

946
947 Plée, K., Ariztegui, D., Martini, R., Davaud, E. (2008) Unravelling the microbial role in ooid
948 formation - results of an in situ experiment in modern freshwater Lake Geneva in
949 Switzerland. *Geobiology* 6, 341-350.

950 Porter, S.M. (2007) Seawater chemistry and early carbonate biomineralization. *Science* 316,
951 1302-1302.

- 952 Pratt, B.R. (1984) *Epiphyton* and *Renalcis*--Diagenetic microfossils from calcification of
953 coccoid blue-green algae. AAPG Bull. 54, 948-971.
- 954 Qi, Y., Meng, Y., Dai, M., Li, D. (2014) Biogenic leopard patch structures from the
955 Zhushadong Formation (Cambrian Series 2), Dengying area, western Henan.
956 Geological Science and Technology Information 33, 1-9.
- 957 Qian, Y., 1999, Taxonomy and Biostratigraphy of Small Shelly Fossils in China. Science
958 Press, Beijing.
- 959 Qian, Y., Li, G., Jiang, Z., Chen, M., Yang, A. (2007) Some phosphatized cyanobacterian
960 fossils from the basal Cambrian of China. Acta Micropalaeontologica Sinica 24, 222-
961 228.
- 962 Regional Stratigraphic Chart Writing Group, 1980, The Volume of Ningxia Hui Autonomous
963 Region, Regional Stratigraphic Chart of Northwestern Area. Geological Publishing
964 House, Beijing.
- 965 Reinhard, C.T., Planavsky, N.J. (2020) Biogeochemical controls on the redox evolution of
966 Earth's oceans and atmosphere. Elements 16, 191-196.
- 967 Richter, D.K., Neuser, R.D., Schreuer, J., Gies, H., Immenhauser, A. (2011) Radial-fibrous
968 calcites: A new look at an old problem. Sedimentary Geology 239, 23-36.
- 969 Riding, R. (1977) Calcified *Plectonema* (blue-green algae), a recent example of *Girvanella*
970 from Aldabra Atoll. Palaeontology 20, 33-46.
- 971 Riding, R. (1982) Cyanophyte calcification and changes in ocean chemistry. Nature 299, 814-
972 815.
- 973 Riding, R., Voronova, L. (1984) Assemblages of calcareous algae near the
974 Precambrian/Cambrian boundary in Siberia and Mongolia. Geological Magazine 121,
975 205-210.
- 976 Riding, R., Voronova, L., (1985) Morphological Groups and Series in Cambrian Calcareous
977 Algae, In: Toomey, D.F., Nitecki, M.H. (Eds.), Paleoalgology: Contemporary
978 Research and Applications. Springer, Berlin, Heidelberg, pp. 56-78.
- 979 Riding, R. (1992) Temporal variation in calcification in marine cyanobacteria. Journal of the
980 Geological Society 149, 979-989.
- 981 Riding, R., Zhuravlev, A.Y. (1995) Structure and diversity of oldest sponge-microbe reefs:
982 Lower Cambrian, Aldan River, Siberia. Geology 23, 649-652.
- 983 Riding, R. (2000) Microbial carbonates: The geological record of calcified bacterial-algal
984 mats and biofilms. Sedimentology 47, 179-214.
- 985 Riding, R., (2001) Calcified algae and bacteria, In: Zhuravlev, A.Y., Riding, R. (Eds.), The
986 Ecology of the Cambrian Radiation. Columbia University Press, New York, pp. 445-
987 473.
- 988 Riding, R., Liang, L. (2005) Geobiology of microbial carbonates: metazoan and seawater
989 saturation state influences on secular trends during the Phanerozoic. Palaeogeogr.
990 Palaeoclimatol. Palaeoecol. 219, 101-115.
- 991 Riding, R. (2006) Cyanobacterial calcification, carbon dioxide concentrating mechanisms,
992 and Proterozoic-Cambrian changes in atmospheric composition. Geobiology 4, 299-
993 316.
- 994 Riding, R., (2011a) Calcified cyanobacteria, In: Reitner, J., Thiel, V. (Eds.), Encyclopedia of
995 Geobiology. Springer Netherlands, Dordrecht, pp. 211-223 English.

- 996 Riding, R., (2011b) Microbialites, stromatolites, and thrombolites, In: Reitner, J., Thiel, V.
997 (Eds.), *Encyclopedia of Geobiology*. Springer Netherlands, Dordrecht, pp. 635-654
998 English.
- 999 Riding, R., Liang, L., Lee, J.-H., Virgone, A. (2019) Influence of dissolved oxygen on secular
1000 patterns of marine microbial carbonate abundance during the past 490 Myr.
1001 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 514, 135-143.
- 1002 Ries, J.B., Anderson, M.A., Hill, R.T. (2008) Seawater Mg/Ca controls polymorph
1003 mineralogy of microbial CaCO₃: A potential proxy for calcite-aragonite seas in
1004 Precambrian time. *Geobiology* 6, 106-119.
- 1005 Ries, J.B. (2010) Review: geological and experimental evidence for secular variation in
1006 seawater Mg/Ca (calcite-aragonite seas) and its effects on marine biological
1007 calcification. *Biogeosciences* 7, 2795-2849.
- 1008 Rowland, S.M., Gangloff, R.A. (1988) Structure and paleoecology of Lower Cambrian reefs.
1009 *Palaaios* 3, 111-135.
- 1010 Rowland, S.M., Shapiro, R.S., (2002) Reef patterns and environmental influences in the
1011 Cambrian and earliest Ordovician, In: Kiessling, W., Flügel, E., Golonka, J. (Eds.),
1012 *Phanerozoic Reef Patterns*. SEPM Special Publication, Tulsa, Okla, pp. 95-128.
- 1013 Sandberg, P.A. (1983) An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy.
1014 *Nature* 305, 19-22.
- 1015 Schirrmeister, B.E., Sanchez-Baracaldo, P., Wacey, D. (2016) Cyanobacterial evolution during
1016 the Precambrian. *Int J Astrobiol* 15, 187-204.
- 1017 Schopf, J.W. (2006) Fossil evidence of Archaean life. *Philosophical Transactions of the Royal*
1018 *Society of London. Series B* 361, 869-885 eng.
- 1019 Seilacher, A., Pflüger, F., (1994) From biomats to benthic agriculture: A biohistoric
1020 revolution, In: Krumbein, W.E., Peterson, D.M., Stal, L.J. (Eds.), *Biostabilization of*
1021 *Sediments*. Bibliotheks and Informationssystem del Carl von Ossietzky Universitat,
1022 Oldenburg, pp. 97-105.
- 1023 Shahkarami, S., Buatois, L.A., Gabriela Mángano, M., Hagadorn, J.W., Almond, J. (2020)
1024 The Ediacaran–Cambrian boundary: Evaluating stratigraphic completeness.
1025 *Precambrian Research* 345, 105721.
- 1026 Shapiro, R.S. (2000) A comment on the systematic confusion of thrombolites. *Palaaios* 15,
1027 166-169.
- 1028 Shi, K., Liu, B., Tian, J., Pan, W. (2016) Sedimentary characteristics and lithofacies
1029 paleogeography of Sinian in Tarim Basin. *Acta Petrolei Sinica* 37, 1343-1360.
- 1030 Song, J., Luo, P., Yang, S., Yang, D., Zhou, C., Li, P., Zhai, X. (2014) Reservoirs of Lower
1031 Cambrian microbial carbonates, Tarim Basin, NW China. *Petroleum Exploration and*
1032 *Development* 41, 449-459.
- 1033 Stanley, S.M. (2008) Effects of global seawater chemistry on biomineralization: past, present,
1034 and future. *Chemical Review* 108, 4483-4498.
- 1035 Stephens, N.P., Sumner, D.Y. (2002) Renalcids as fossilized biofilm clusters. *Palaaios* 17, 225-
1036 236.
- 1037 Sun, X., Heubeck, C., Steiner, M., Yang, B. (2020a) Environmental setting of the Cambrian
1038 Terreneuvian rocks from the southwestern Yangtze Platform, South China.
1039 *Palaeogeography, Palaeoclimatology, Palaeoecology* 538.

1040 Sun, X., Heubeck, C., Steiner, M., Yang, B. (2020b) Environmental setting of the Cambrian
1041 Terreneuvian rocks from the southwestern Yangtze Platform, South China.
1042 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 538, 537-550.

1043 Tang, H., Kershaw, S., Tan, X.-C., Liu, H., Li, F., Shen, C., Lu, F.-F., Yang, X.-F. (2019)
1044 Sedimentology of reefal buildups of the Xiannüdong Formation (Cambrian Series 2),
1045 SW China. *J Palaeogeog* 8, 11 English.

1046 Torsvik, T.H., Cocks, L.R.M., From Harper, D.A.T., Servais, T. (2013) New global
1047 palaeogeographical reconstructions for the Early Palaeozoic and their generation.
1048 *Geol. Soc. Lon. Mem.* 38, 5-24.

1049 Turner, E.C., James, N.P., Narbonne, G.M. (2000) Taphonomic control on microstructure in
1050 early Neoproterozoic reefal stromatolites and thrombolites. *Palaios* 15, 87-111.

1051 Visscher, P.T., Stolz, J.F. (2005) Microbial mats as bioreactors: Populations, processes, and
1052 products. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 219, 87-100.

1053 Wan, B., Tang, Q., Pang, K., Wang, X., Bao, Z., Meng, F., Zhou, C., Yuan, X., Hua, H., Xiao,
1054 S. (2019) Repositioning the Great Unconformity at the southeastern margin of the
1055 North China Craton. *Precambrian Research* 324, 1-17.

1056 Ward, L.M., Kirschvink, J.L., Fischer, W.W. (2016) Timescales of oxygenation following the
1057 evolution of oxygenic photosynthesis. *Orig Life Evol Biosph* 46, 51-65.

1058 Wei, G.-Y., Planavsky, N.J., He, T., Zhang, F., Stockey, R., Cole, D.B., Lin, Y.-B., Ling, H.-F.
1059 (2021) Global marine redox evolution from the late Neoproterozoic to the early
1060 Paleozoic constrained by the integration of Mo and U isotope records. *Earth-Science*
1061 *Reviews* 214, 103506.

1062 Wilkinson, B.H., Owen, R.M. (1985) Submarine hydrothermal weathering, global eustasy,
1063 and carbonate polymorphism in Phanerozoic marine oolites. *Journal of Sedimentary*
1064 *Research* 55, 171-183.

1065 Wood, R., Zhuravlev, A.Y., Anaaz, C.T. (1993) The ecology of Lower Cambrian buildups
1066 from Zuune Arts, Mongolia: Implications for early metazoan reef evolution.
1067 *Sedimentology* 40, 829-858.

1068 Wood, R., Liu, A.G., Bowyer, F., Wilby, P.R., Dunn, F.S., Kenchington, C.G., Cuthill, J.F.H.,
1069 Mitchell, E.G., Penny, A. (2019) Integrated records of environmental change and
1070 evolution challenge the Cambrian Explosion. *Nature Ecology & Evolution* 3, 528-
1071 538.

1072 Wood, R.A., Zhuravlev, A.Y., Sukhov, S.S., Zhu, M., Zhao, F. (2017) Demise of Ediacaran
1073 dolomitic seas marks widespread biomineralization on the Siberian Platform.
1074 *Geology* 45, 27-30.

1075 Wu, H., Zhao, Z., Wang, J., Wang, P., Gong, F., Xiao, F. (2018) Cambrian sequence
1076 stratigraphic framework in northern margin of North China Craton. *Journal of Jilin*
1077 *University (Earth Science Edition)* 48, 1609-1624.

1078 Xiao, S., Bao, H., Wang, H., Kaufman, A.J., Zhou, C., Li, G., Yuan, X., Ling, H. (2004) The
1079 Neoproterozoic Quruqtagh Group in eastern Chinese Tianshan: evidence for a post-
1080 Marinoan glaciation. *Precambrian Research* 130, 1-26.

1081 Xiao, S., Chen, Z., Zhou, C., Yuan, X. (2019) Surfing in and on microbial mats: Oxygen-
1082 related behavior of a terminal Ediacaran bilaterian animal. *Geology* 47, 1054-1058.

- 1083 Xiao, S.H., Narbonne, G.M., (2020) The Ediacaran Period, In: Gradstein, F.M., Ogg, J.G.,
1084 Schmitz, M.D., Ogg, G.M. (Eds.), *Geologic Time Scale 2020*. Elsevier, pp. 521-561.
- 1085 Xu, B., Xiao, S., Zou, H., Chen, Y., Li, Z., Song, B., Liu, D., Zhou, C., Yuan, X. (2009)
1086 SHRIMP zircon U–Pb age constraints on Neoproterozoic Quruqtagh diamictites in
1087 NW China. *Precambrian Research* 168, 247-258.
- 1088 Xue, Y., Zhou, C. (2006) Resedimentation of the early Cambrian phosphatized small shell
1089 fossils and correlation of the Sinian–Cambrian boundary strata in the Yangtze region,
1090 southern China. *Journal of Stratigraphy* 30, 64-75.
- 1091 Yang, A., (2005) *The Early Cambrian Archaeocyaths and Their Extinction Event on the*
1092 *Yangtze Platform*. Graduate School of Chinese Academy of Sciences, Nanjing, p.
1093 234.
- 1094 Yang, A., Yuan, K. (2012) New archaeocyaths from the early Cambrian of Shaanxi and
1095 Guizhou provinces, South China. *Geobios* 45, 591-601.
- 1096 Yang, A., Zhu, M., Zhuravlev, A.Y., Yuan, K., Zhang, J., Chen, Y. (2016) Archaeocyathan
1097 zonation of the Yangtze Platform: Implications for regional and global correlation of
1098 lower Cambrian stages. *Geological Magazine* 153, 388-409.
- 1099 Yue, Z., Gao, L., Qiao, X., Liu, G. (1990) On the age of the lower boundary of the Cambrian
1100 and the lower Cambrian sedimentary environment in Tonghua, Jilin Province.
1101 *Geological Review* 36, 229-238.
- 1102 Yun, H., Zhang, X., Li, L., Zhang, M., Liu, W. (2016) Skeletal fossils and microfacies
1103 analysis of the lowermost Cambrian in the southwestern margin of the North China
1104 Platform. *J. Asian Earth Sci.* 129, 54-66.
- 1105 Zeng, K., Li, F., Gong, Q., Tang, H., Su, C., Che, Z., Deng, J., Hu, G., Li, L., Zeng, W., Tan,
1106 X. (2020) Characteristics and paleoenvironmental significance of mixed
1107 siliciclastic-carbonate sedimentation in the Xiannüdong Formation, Cambrian (Series
1108 2): A case study from the Tangjiahe section, Wangcang, northern Sichuan. *Acta*
1109 *Sedimentol. Sinica* 38, 166-181.
- 1110 Zhai, X., Luo, P., Gu, Z., Jiang, H., Zhang, B., Wang, Z., Wang, T., Wu, S. (2020) Microbial
1111 mineralization of botryoidal laminations in the Upper Ediacaran dolostones, Western
1112 Yangtze Platform, SW China. *J. Asian Earth Sci.* 195, 104334.
- 1113 Zhang, G., Guo, A., Wang, Y., Li, S., Dong, Y., Liu, S., He, D., Cheng, S., Lu, R., Yao, A.
1114 (2013) Tectonics of South China continent and its implications. *Science China Earth*
1115 *Sciences* 56, 1804-1828.
- 1116 Zhang, H., Lu, W., Yang, H., Ni, X., Shen, A., 2017a, *Atlas of Geological Sections of*
1117 *Cambrian-Ordovician Marine Carbonate Reservoir in Tarim Basin*. Petroleum
1118 Industry Press, Beijing.
- 1119 Zhang, J., Zhou, Y., Qiu, J. (1981) Palaeoenvironmental implication of the leopard limestones
1120 of the lower Cambrian Changping Formation in the Yanshan area. *Journal of*
1121 *Stratigraphy* 5, 50-58.
- 1122 Zhang, J., Yuan, K. (1994) Archaeocyath reefs from the lower Cambrian Tianheban
1123 Formation at Wangjiaping, Yichang, Hubei and their diagenesis. *Scientia Geologica*
1124 *Sinica* 29, 236-245.

- 1125 Zhang, M., Hong, J., Choh, S.-J., Lee, D.-J. (2017b) Thrombolite reefs with archaeocyaths
1126 from the Xiannüdong Formation (Cambrian Series 2), Sichuan, China: implications
1127 for early Paleozoic bioconstruction. *Geosciences Journal* 21, 655-666.
- 1128 Zhang, S., Sun, C. (1991) Early Cambrian small shelly fossils from Chaohu area, Anhui. *Acta*
1129 *Micropalaeontologica Sinica* 8, 19-40.
- 1130 Zhang, W., Zhu, Z. (1979) Notes on some trilobites from the lower Cambrian Houjiashan
1131 Formation in southern and southwestern parts of North China. *Acta Palaeontologica*
1132 *Sinica* 18, 513-525.
- 1133 Zhang, Y., Yin, L., Xiao, S., Knoll, A.H. (1998) Permineralized Fossils from the Terminal
1134 Proterozoic Doushantuo Formation, South China. *The Paleontological Society*
1135 *Memoir* 50, 1-52.
- 1136 Zhang, Y., Yang, T., Hohl, S.V., Zhu, B., He, T., Pan, W., Chen, Y., Yao, X., Jiang, S. (2020)
1137 Seawater carbon and strontium isotope variations through the late Ediacaran to late
1138 Cambrian in the Tarim Basin. *Precambrian Research* 345, 105769.
- 1139 Zhang, Z., Liu, M., 1996, Stratigraphy (Lithostratic) of Shandong Province. China University
1140 of Geosciences Press, Wuhan.
- 1141 Zheng, B., (2016) Sequence-based Lithofacies Paleogeography and Favorable Facies Belt of
1142 Reservoir Prediction of Early Cambrian Longwangmiao Age in Guizhou Area. China
1143 University of Geosciences, Beijing, p. 59.
- 1144 Zheng, H., Hu, Z., 2010, Atlas of Pre-Mesozoic Tectonic Lithofacies Paleogeography in
1145 China. Geological Publishing House, Beijing.
- 1146 Zhou, C., Yuan, X., Xiao, S., Chen, Z., Hua, H. (2019) Ediacaran integrative stratigraphy and
1147 timescale of China. *Science China Earth Sciences* 62, 7-24.
- 1148 Zhou, Z., 2001, Stratigraphy of the Tarim Basin. Science Press, Beijing.
- 1149 Zhu, M.Y., Yang, A.H., Yuan, J.L., Li, G.X., Zhang, J.M., Zhao, F.C., Ahn, S.Y., Miao, L.Y.
1150 (2019) Cambrian integrative stratigraphy and timescale of China. *Sci. China Earth*
1151 *Sci.* 62, 25-60 English.
- 1152 Zhuravlev, A.Y., Wood, R. (1995) Lower Cambrian reefal cryptic communities. *Palaeontology*
1153 38, 443-470.
- 1154 Zhuravlev, A.Y. (1996) Reef ecosystem recovery after the Early Cambrian extinction.
1155 Geological Society, London, Special Publications 102, 79-96.
- 1156 Zhuravlev, A.Y., (2001) Paleocology of Cambrian Reef Ecosystems, In: Stanley, G.D. (Ed.),
1157 The History and Sedimentology of Ancient Reef Systems. Springer US, Boston, MA,
1158 pp. 121-157.
- 1159 Zhuravlev, A.Y., Wood, R.A. (2008) Eve of biomineralization: Controls on skeletal
1160 mineralogy. *Geology* 36, 923.

1161

1162

1163 **Figure captions**

1164

1165 Fig. 1 (A) Outline map of China showing the three major blocks (i.e., North and South China,
1166 and Tarim). (B) Global paleogeography in the Ediacaran-Cambrian transition (ca. 540 Ma),
1167 with the location of the North China (NCB), South China, and Tarim blocks. Base map after
1168 Torsvik et al. (2013). (C) The timescale and the regional biostratigraphic correlation in three
1169 blocks from the uppermost Ediacaran to the lower Cambrian. Chronostratigraphic data from
1170 Zhou et al. (2019) and Zhu et al. (2019); biostratigraphic zones from Zhu et al. (2019) and Peng
1171 et al. (2020); carbon-isotope chemostratigraphic markers from Zhu et al. (2019), and Xiao and
1172 Narbonne (2020). Note that three types of biozones are in black (trilobite), blue (small shelly
1173 fossil), and pink (archaeocyath) colors, respectively. Abbreviations: *A.* = *Archaeocyathus*;
1174 AECE = Archaeocyathid Extinction Carbon isotope Excursion; BACE = Basal Cambrian
1175 Carbon isotope Excursion; CARE = Cambrian Arthropod Radiation isotope Excursion; MICE
1176 = Mingxinsi Carbon isotope Excursion; *P.* = *Palaeolenus*; ROECE = Redlichiid-Olenellid
1177 Extinction Carbon isotope Excursion; U. = Uppermost.

1178

1179 Fig. 2 Terminal Ediacaran paleogeography of China (ca. 550–540 Ma), with the distribution of
1180 microbialites. Base map adapted from Zheng and Hu (2010). Site information of microbialite
1181 development is shown in Table S1. Study sections in the text: E1 = Daheba; E2 = Micangshan;
1182 E3 = Changyangou; E4 = Xiaotan; E5 = Xigou; E6 = Sugetbrak; and E7 = Shiirik.

1183

1184 Fig. 3 Early Cambrian paleogeography of China (ca. 540–509 Ma), with the distribution of
1185 microbialites. Base map adapted from Zheng and Hu (2010). Site information of microbialite
1186 development is shown in Table S1. Study sections in the text: C1 = Xigou; C2 = Daheba; C3 =
1187 Fucheng; C4 = Shatan; C5 = Tangjiahe; C6 = Limei; C7 = Dilong; C8 = Dingtai; and C9 =
1188 Yankong.

1189

1190 Fig. 4 Field photographs of the uppermost Ediacaran microbialites. (A) Columnar (lower) and
1191 domical (upper) stromatolites. Lower Chigebrak Formation, Xigou section. (B) Plan view of
1192 the yellow dashed box in (A), showing the top-surface of numerous domical stromatolites. (C)
1193 Massive stratiform stromatolites with nearly parallel millimeter-level laminated structures.
1194 Dengying Formation, Daheba section. (D) Thick-bedded stratiform stromatolites composed of
1195 rippled and wavy laminae (arrowed), and some cement-filled cavities along the laminar
1196 direction. Dengying Formation, Xiaotan section. (E) Reworked stratiform stromatolites with
1197 irregularly laminated structures. Dengying Formation, Changyangou Section. (F) A
1198 stromatolitic microbialite with some narrow-laminar and patchy structures (clotted
1199 microstructures). Xiaerbrak Formation, Xigou Section. (G) Alternating laminated and clotted
1200 structures in a composite microbialite with a complex cavity system. Dengying Formation,
1201 Micangshan Section. (H) Enlarged clotted structures of the sample place (G) showing the
1202 microclots (yellow arrows) and the complex cavity network (pink arrows).

1203

1204 Fig. 5 Polished slabs of the uppermost Ediacaran microbialites (**vertical sections**). (A) Regularly
1205 laminated structures in a stromatolite. Dengying Formation, Xiaotan section. (B-C)
1206 Intermingled laminated and clotted structures in a thinly bedded microbialite with two large
1207 cavities (arrowed). Dengying Formation, Changyangou section. (D) Alternating laminated and
1208 clotted structures in a composite microbialite with abundant cavities. The cavities generally
1209 consist of coarse-crystalline cements and micritic rims. Dengying Formation, Micangshan
1210 section. (E) A clotted framework in a thrombolite with large numbers of cavities. Upper
1211 Chigebrak Formation, Xigou section. (F) Composite laminated and clotted structures in a
1212 microbialite with a complex cavity system (arrowed). Upper Chigebrak Formation, Shiairik
1213 section. (G) A clotted framework in a thrombolite with irregularly grown cavities filled with
1214 coarse spar (arrowed). The clots are composed of large numbers of solid and hollow peloidal
1215 clusters (see [Fig. 8C and D](#)). Upper Chigebrak Formation, Xigou section. (H) A clotted
1216 framework in a thrombolite. The clotted structures consist of large quantities of dense
1217 microclots with diameter of 0.1-0.2 mm (arrowed; for the microstructure, see [Fig. 8E](#)).
1218 Dengying Formation, Xiaotan section.

1219

1220 Fig. 6 Field photographs of the Cambrian microbialites. (A) Small columnar stromatolites.
1221 Basal Yurtus Formation (Fortunian). Sugetbrak section. (B) Stratiform and small domical
1222 stromatolites. Longwangmiao Formation (Stage 4), Yankong section. (C) Alternating oolitic
1223 (thickness of 1-2 cm) and stromatolitic (thickness of 0.5-1 cm) beds. Qingxudong Formation
1224 (Stage 4), Dilong section. (D) A calcimicrobial–archaeocyath bioherm developed in a mixed
1225 siliciclastic-carbonate depositional system. The inset box in the upper right shows the

1226 characteristics of archaeocyaths (arrowed) and detrital fractions. Xiannüdong Formation (lower
1227 part of Stage 3), Daheba section. (E) Clotted structures in a thrombolite, with some detrital silt
1228 fractions. (F) Fan-like (thin branches; bushy) clots in a thrombolite. (E) and (F) from the
1229 Xiannüdong Formation of the Shatan section. (G) Dendritic structures preserved in a massive
1230 thrombolite. Xiannüdong Formation, Tangjiahe section. (H) Dendritic structures (0.5-1 cm in
1231 width) preserved in a thrombolite **and composed of filamentous cyanobacteria microfossils**.
1232 Growth orientation of the branched dendritic structures is marked by arrows. Qingxudong
1233 Formation (Stage 4), Limei section.

1234

1235 Fig. 7 Polished slabs of the Cambrian microbialites (**vertical sections**). (A) Columnar
1236 stromatolite. Basal Yurtus Formation (Fortunian). Sugetbrak section. (B) Stratiform
1237 stromatolite with nearly-parallel laminated structures. Longwangmiao Formation (Stage 4).
1238 Yankong section. (C) Alternating laminated and clotted structures showing the preservation of
1239 tubiform microfossils (arrowed). Lower Qingxudong Formation (Stage 4), Limei section. (D-
1240 G) Different types of clotted structures in the **calcimicrobial–archaeocyath** bioherms of the
1241 Xiannüdong Formation (lower Stage 3). **The white dotted lines in (D), (E), and (G) indicate the**
1242 **boundaries between the calcimicrobial–archaeocyath structures and terrigenous fine-grained**
1243 **particles**. Arch. = archaeocyath. (D) and (G) from the Shatan section; (E) from the Daheba
1244 section; and (F) from the Fucheng section. (H) Clotted structures showing erected dendritic
1245 characteristics, with large quantities of calcified microbial microfossils (see [Fig. 9G](#)). Lower
1246 Qingxudong Formation, Limei section.

1247

1248 Fig. 8 Thin-section photomicrographs of the uppermost Ediacaran microbialites. (A)
1249 Irregularly-arranged laminated structures in a stromatolite. The dark-colored layers are
1250 cryptocrystalline and consist of mimetic dolomite crystals (generally $<2\ \mu\text{m}$); the light-colored
1251 layers are generally composed of medium- to fine-grained dolomite grains ($4\text{--}40\ \mu\text{m}$).
1252 Dengying Formation, Changyangou section. (B) Well-cemented clotted microstructures in a
1253 thrombolite. The clots are shown as dark-colored, cryptocrystalline aggregate grains with no
1254 visible microfossils. The early-stage cements are composed of fibrous to acicular, isopachous
1255 dolomite crystals; the late-stage cements consist of pore-filling, subhedral to anhedral, coarse
1256 dolomite crystals (generally $100\text{--}500\ \mu\text{m}$). Some clots show the occurrence of dolomite
1257 inclusions. Dengying Formation, Micangshan section. (C) Closely-packed clotted structures in
1258 a thrombolite. The clots are composed of large quantities of hollow peloidal clusters, with
1259 isopachous crusts and coarse cavity-filling cements. Upper Chigebrak Formation, Xigou
1260 section. (D) Enlargement of the box in (C) showing the micritic (organic-rich) walls and
1261 recrystallized chambers of the peloidal microstructures. (E) Clotted structures showing
1262 numerous dark-colored microclots connected with each other through micritic networks.
1263 Dengying Formation, Xiaotan section. (F) Enlarged microclots of the same thin-section (E)
1264 showing the occurrence of tens of micrometer granular aggregates with no visible microbial
1265 microfossils. (G) Clotted structures in a strongly diagenetically altered thrombolite. The clotted
1266 structures consist of the fibrous and microcrystalline dolomite crystals, and the chambered
1267 relics. Chigebrak Formation, Xigou section. (H) Clotted structures in a **weakly** diagenetically
1268 altered thrombolite when compared to (G). The clots contain plentiful granular aggregates and

1269 are filled by medium to finely grained dolomite crystals (red arrows), and medium to coarsely
1270 grained calcite crystals (yellow arrows). Chigebrak Formation, Xigou section.

1271

1272 Fig. 9 Thin-section photomicrographs of the Cambrian microbialites. (A) Stromatolitic
1273 structures preserved in the siliceous phosphorite. Basal Yurtus Formation (Fortunian), Shiairik
1274 section. (B) *Microdigitate*-columnar stromatolite exhibiting a convex-upward laminated
1275 structure. Enlargement of the arrowed position showing the distribution of filamentous
1276 *Girvanella* microfossils. Xiannüdong Formation (Stage 3), Fucheng section. (C) Clotted
1277 structures composed of plentiful *Epiphyton* microfossils within a thrombolitic mound.
1278 Xiannüdong Formation, Tangjiahe section. (D) *Renalcis*-dominant microfossils developed in
1279 the clotted structures of a thrombolitic mound. Some *Tarthinia* microbes (arrowed) are
1280 associated with the *Renalcis* group. Xiannüdong Formation, Tangjiahe section. (E) A branched
1281 microfossil (lower left box) with radiating fans composed of separated tubes, possibly a
1282 *Hedstroemia* group. Lower Qingxudong Formation (Stage 4), Dingtai section. (F) Well-formed,
1283 tubiform microfossils (clotted forms) with a series of irregular tangled tubes (lower right box),
1284 possibly a *Botomaella* group. Lower Qingxudong Formation (Stage 4), Limei section. (G) Well-
1285 cemented clotted structures composed of large numbers of *Epiphyton* microfossils. Lower
1286 Qingxudong Formation, Limei section. Note that their widths and lengths are much larger than
1287 those in Stage 3 (see [Results section](#)). (H) Clotted structures preserved in a thrombolitic mound
1288 in the upper Xiaerbrak Formation (upper part of Stage 3) with some possible microbial
1289 microfossils (arrowed). This type of fossil is presumably a *Tarthinia* group. Xigou section.

1290

1291 Fig. 10 Mineralogical characteristics of the ooids and calcified microbes in Cambrian Stages
1292 3–4. (A–B) Association of ooids and calcified microbes in the lower part of Stage 3. Ooids are
1293 characterized by well preserved (stained), radial-concentric fabrics (arrowed); *Renalcis* group
1294 shows well-formed cryptocrystalline botryoidal structure. The microstructures and Mg-Sr data
1295 (see [Section 5.3.1](#)) indicate a primary calcite mineralogy. (A) from the Xiannüdong Formation
1296 (lower part of Stage 3), Tangjiahe section; (B) from the Xiannüdong Formation, Daheba section.
1297 (C) Rare *Epiphyton* microfossils showing the appearance of dolomite inclusions within their
1298 calcified structures. Lower Xiannüdong Formation, Tangjiahe section. (D) Association of ooids
1299 and the stromatolitic structure in the upper part of Stage 4. Strongly altered ooids (arrowed) and
1300 microbial laminated structures; their primary fabrics were recrystallized during diagenesis.
1301 Upper Qingxudong Formation (upper part of Stage 4), Dingtai Section. (E) Photomicrograph
1302 of clotted structures in a thrombolite specimen, with no visible calcified microfossils. Upper
1303 Qingxudong Formation, Dilong section. (F) Poorly preserved ooid grains with weakly-radial
1304 and completely-recrystallized cortical fabrics. Upper Qingxudong Formation, Dingtai Section
1305

1306 Fig. 11 Cartoon diagram showing the depositional environments for the thrombolites and
1307 stromatolites in the latest Ediacaran (A) and the early Cambrian (B). Note: the development of
1308 columnar and domical stromatolites does not appear to have been affected in the transition; the
1309 presence of stratiform stromatolites in the open shelf environment markedly decreased in the
1310 Cambrian likely caused by increasing bioturbation in the seafloor sediments. The thrombolites

1311 evolved to form mound-like shapes and **branching forms (fan-like/dendritic textures)**, possibly
1312 adapted to increasing bioturbation, hydrodynamic condition, and O₂ production rate. Not to
1313 scale.

1314

1315 Fig. 12 (A) Number of occurrences of the microbialites (stromatolites and thrombolites) and
1316 calcified **microbial** microfossils (within microbialites) from the uppermost Ediacaran to
1317 Cambrian Series 2 in China. Original data are synthesized in [Table S1](#). (B) Total genera of the
1318 calcified microfossils (including cyanobacteria and suspected cyanobacteria) in the lower
1319 Cambrian. Data from Riding (2001). (C) Net atmospheric O₂ production, and net marine
1320 primary productivity. Data from Wei et al. (2021). The development of microbialites and
1321 diversity of calcified microbes are roughly consistent with the higher rates of atmospheric O₂
1322 production and marine primary productivity during the Ediacaran-Cambrian transition. (D) The
1323 evolution of seawater Mg/Ca molar ratio in the Ediacaran-Cambrian transition. Curve redrawn
1324 using the data of fluid inclusions (squared) in marine halite ([Brennan et al., 2004](#); [Petrychenko](#)
1325 [et al., 2005](#)). The intervals of aragonite-dolomite sea, aragonite sea, and calcite sea in the
1326 Ediacaran-Cambrian transition are from Wood et al. (2017) and references therein. The
1327 empirical estimates of the primary non-skeletal mineralogical compositions are from Stanley
1328 (2008). The primary mineralogies of ooids in this study conform to the seawater Mg/Ca
1329 compositions.

1330

1331