
28 speleothems, chalcedony, and quartz should have filled sheet-cracks during the uplift,
29 karstification, and subsequently hydrothermal processes before the secondary
30 transgression. Thus these widely distributed paleo-speleothems, which are direct
31 geological evidence for the ‘greening’ Earth in the early Ediacaran, might represent an
32 initial formation of the soil-ecosystem after the barren snowball Earth.

33 **1. Introduction**

34 Paleo-climate evolution in the Neoproterozoic (1,000-542 Ma), the most notable
35 of which was the abrupt climate transition in the aftermath of the Marinoan deglaciation
36 (~635 Ma ⁴) recorded in the 3-5 m cap dolostones and its idiosyncratic sedimentary
37 structure, was the prelude to the Cambrian explosion. Isotopic studies ¹⁻³ have described
38 a rapid evolution from a snowball Earth to a 'greening' Earth, which could greatly
39 enhance groundwater influx of photosynthetic carbon from phytomass and promote the
40 'clay mineral factory', and then subsequently increase the atmosphere's O₂ content ⁵ and
41 trigger the expansion of multicellular life. This rapid evolution centered on a drastic
42 change of the continental weathering mode which elevated the bio-available P flux and
43 promoted the marine primary productivity. Therefore, geological records of
44 contemporaneous continental weathering are important clues to understanding the
45 evolution of life in the Neoproterozoic and to illuminating the Cambrian explosion.

46 Karstification is the most important continental weathering process in carbonate
47 distribution zones, of which the environment change could be record by speleothems
48 (stalagmites, stalactites, flowstones etc.). Studies of modern karst caves suggest that
49 speleothem deposition is mostly controlled by evolution of CO₂ contents in drip-water,
50 which originate from precipitation (atmospheric CO₂) and supersaturation in soil zone
51 (CO₂ from bio-respiration and organic decomposition) and then degassing in caves ⁶⁻⁸.
52 Thus paleo-speleothems in paleo-karst, such as dripstone ⁹, micro-stalactite ^{10,11} and
53 stromatolitic laminae coatings ¹², are significant evidence for subaerial exposure and
54 paleo-pedogenesis. The widespread discontinuous karstic surface at the top of cap

55 dolostones (635 Ma) in Africa, Canada and China has disclosed a global karstic
56 dissolution event ¹³ caused by uplifting of continental shelf responding to deglacial
57 isostatic rebound ¹⁴. Hence, more detailed geological evidence such as paleo-
58 speleothems are expected to be preserved in fissures, voids and sheet-cracks related to
59 the karstic dissolution event ¹³.

60 In this paper, we report a series of miniature but delicate paleo-speleothems
61 (including stalagmites, stalactites and coatings) preserved in the sheet-crack of
62 Marinoan cap dolostone (~635 Ma) in South China. These paleo-speleothems further
63 confirm the possibility of a broad and transient continental uplift with exposure and
64 continental weathering due to the deglacial isostatic rebound.

65 **2. Geological setting and observations**

66 The Doushantuo Formation of basin, slope and platform facies is widely deposited
67 on the Yangtze Block of South China (see Fig.1 in ref. ¹³), and is underlain by Marinoan
68 deglacial tillite unit. This shows a transition from purple diamictite (<100 m) in platform
69 facies to grey diamictite (>1000 m) in basin facies. The 3-5 m cap dolostone in basal
70 Doushantuo Formation from platform to slope facies is significant with disrupted
71 massive dolomicrite and unique structures (such as giant wave ripples ¹⁵, teepee-like,
72 sheet-cracks etc. ¹⁶). A broadly karstic dissolution surface, caused by uplift by isostatic
73 rebound, has been confirmed by geological observation in South China. The total
74 duration (<1.0 Ma) from deposition to exposure and dissolution of the cap dolostone
75 has been constrained by high-precision U-Pb zircon age of 634.57 ± 0.88 Ma at the
76 topmost of Nantuo diamictite ⁴ and 635.23 ± 0.57 Ma at the topmost of cap dolostone
77 ^{17,18}, respectively. Remarkably, sheet-cracks have a uniform mineral paragenetic
78 sequence across the entire Yangtze Block: they start with isopachous dolomites
79 (sometimes with minor barite), followed by siliceous minerals (chalcedony and quartz),
80 and ending with later stage calcite and barite ¹⁹.

81 Miniature but perfect stalactites and stalagmites, which are the most typical

82 calcareous speleothems (gravitational dripping water forms) (Fig.1, Fig.2), have been
83 gradually disclosed in chalcedony cements from thick (more than 2-3 cm) sheet-cracks
84 of cap dolostones and distributing from slope (Wenghui and Daping) to platform facies
85 (Xiaofenghe and Beidoushan) sections on the Yangtze Block. Based on this discovery,
86 flat and thinner laminae, partly with botryoidal structures, that extensively encrust the
87 ceiling and floor of the sheet-cracks or breccias (Fig.3), have been interpreted here as
88 coatings (non-gravitational water-film forms).

89 **2.1 stalactite**

90 Many stalactites, hanging downwards from the ceiling of sheet-cracks and
91 exhibiting as single one or conjoined by multi-stalactites, have been found in the
92 Beidoushan and Wenghui sections (Fig. 1, 2a, 2e and 2d). The most common individual
93 stalactites are elongated columns, ranging from less than 0.4 cm to about 1.0 cm in
94 diameter, and from less than 1 cm to more than 3 cm in length.

95 Three growth stages could be identified by laminae rhythm in two vertical profiles
96 of stalactites from the Beidoushan section (Fig.1). The first is the straight soda-straw
97 with a central channel. The channel is about 100 μm in diameter and 1-2 cm in length
98 and is lined by brown organisms and filled with cryptocrystalline chalcedony. The wall
99 of the soda-straw is comprised of fibrous chalcedony with about 400-500 μm thickness
100 and it is also coated by brown organisms. The second stage is distinguished by density
101 rippling lamina couplets in flank and botryoid structures in the tip, which reflect stable
102 and slow feeding. The final stage is composed of relative broader lamina couplets which
103 reflect continuous and affluent feeding.

104 The cross-profiles of stalactites are distinguished by multilayer concentric
105 circularity structures with alternations from dark to light. The significant difference,
106 however, is the soda-straw structure, which is generally present in stalactites but
107 absolutely absent in stalagmites. The three growth stages described above can be clearly
108 observed in the cross-profiles of stalactites from the Beidoushan section. In the
109 Wenghui section, however, only two growth stages are displayed in the cross-profiles

110 of stalactites (Fig.2a, 2e and 2d) and in the vertical-profile of stalagmites. These
111 differences suggest that the two sections have different paleo-environments.

112 **2.2 stalagmite**

113 Some stalagmites, which grow upwards from the floor of the sheet-crack, were
114 discovered in Wenghui, Xiaofenghe and Beidoushan sections. They are mainly
115 composed of translucent chalcedony, which makes them obviously distinguished from
116 the surrounding white crystalline quartz in hand-specimens of the Wenghui and
117 Beidoushan sections (Fig.2b, 2d and 2f). Most of them are cylindric in shape, slightly
118 wider in the root and narrower in the tip, with length concentrated around 1-3.5 cm and
119 diameters of about 0.5-1.3 cm. This thin diameter style, classified as "Minimum-
120 diameter" stalagmite²⁰, is coincident with the short drip fall height²¹ in the sheet-cracks.

121 A perfect vertical profile of stalagmite from the Wenghui section shows a clear
122 transition of growth style (Fig.2b) under a reflecting light microscope, while, such a
123 transition is relatively blurred under transmitted light. The early growth style is
124 distinguished by a stacked botryoid structure, which could be observed in the bottom
125 part of modern stalagmites²²⁻²⁵ (Fig.2b) and which represent turbulence of the dripping
126 water at the beginning of stalagmite deposition or indigent feeding and slow
127 precipitation²⁶. The later growth is significant with continuous and smooth rhythmical
128 laminae couplets by a dark and a light lamina, which is similar to modern calcareous
129 stalagmites^{25,27,28} and which represent affluent feeding and stable precipitation^{22,29-31}.
130 The rhythmical laminae are about 350 μm thick and contain about 20-30 lamina
131 couplets.

132 There is one complete stalagmite and three complete stalactite cross-profiles in the
133 same slide, the latter of which are characterized by a central channel texture (Fig.2d).
134 There are two growth stages. The first of these is typical of unity cryptocrystalline
135 chalcedony and the latter of them is features concentric fibrous chalcedony laminae,
136 corresponding to the two-growth style in the vertical profile as mentioned above
137 (Fig.2b). There are about 20-30 laminae couplets within the 2100 μm thick outer zone

138 and this is rich in organics as seen by the obvious increase in fluorescence (Fig.2c, 2e
139 and 2f) when compared to the inner zone. Significantly, residue calcite core and laminae
140 have been observed in one stalagmite cross-profile from the Xiaofenghe section
141 (Fig.3h).

142 **2.3 coatings**

143 In almost all of the cap dolostone sections in South China, the wall (mainly
144 composed of ceiling and floor) of the sheet-cracks and the breccias in them are
145 extensively covered with less than 0.1 cm to 1 cm thick chalcedony coatings, which
146 tend to have fairly continuous layers, and are characterized by visible rippled growth
147 morphology and stacked layering (Fig. 3). Remarkably, partly silicified calcite coatings,
148 which could be distinguished under reflected light and scanning electron microscope
149 (SEM) (Fig.3e and 3f), was preserved in the Daping section. The coatings may be
150 botryoidal (Fig. 3b), or even spiral (looks like vermiform helictites) (Fig.3c and 3d),
151 but in most cases they are smoothly curving along the wall of the sheet-crack and the
152 breccias with stable thickness (Fig. 3a). On the whole, the coatings comprise of 15-30
153 lamina couplets, which are much more obvious in ultraviolet fluorescent (Fig.2c and
154 3g), with single couplet thickness ranging from 20 μm to 60 μm . These morphology
155 and laminae structure indicate that the smooth coatings periodically precipitated from
156 adhesive water-films condensed from humid caves, the botryoidal structure are
157 produced by surface tension dividing water-films into drops and the vermiform
158 helictites produced by the addition of drip water to already present water-films.

159 **3. Discussion**

160 Protogenetic siliceous speleothems are commonly developed in caves or lava
161 tunnels overlain by silicate rocks (such as quartzites, sandstones, granites etc.)³².
162 Although platform-wide black shale overlaid on the cap dolostone³³ seems to be a
163 potential silica source, lack of karstic surface and weathering dissolution textures in the
164 black shale suggests that the sheet-crack speleothems were not protogenetic siliceous

165 speleothems and were constrained before the deposition of the black shale. Indeed, the
166 sheet-crack speleothems are confined below the widespread paleo-karstic surface the
167 age of which has been previously determined by two ash beds with zircon U-Pb age of
168 634.57 ± 0.88 Ma and 635.23 ± 0.57 Ma^{17,18} respectively. Additionally, the coatings in
169 the Daping section are mostly consisted of calcareous laminae (Fig. 3e and 3f) and the
170 silicified stalactites in Xiaofenghe section still retain a few calcareous laminae (Fig. 3h).
171 Therefore, the sheet-crack speleothems deposited at ca. 635Ma were originally
172 calcareous speleothems, which is akin to modern silicification-preserved speleothems
173 formed by low-temperature metasomatism of primary calcareous speleothems^{34,35}.

174 Three successive events associated with the Marinoan cap dolostone in South
175 China have been summarized as such¹³: (1) the first postglacial transgression and
176 deposition of the cap dolostone; (2) isostatic rebound, uplift and karstification of the
177 cap dolostone; and (3) the second postglacial transgression, multiphase cave fillings
178 and post-cap deposition. Multiple mineral generations on walls of sheet-cracks are
179 attributed to the beginning of the second postglacial transgression¹³ or a low-
180 temperature hydrothermal episode^{19,36}, however, minerals corresponding to the uplift
181 and karstification event have not been depicted. No obvious dissolution phenomena by
182 later erosion have been observed on the surface of the paleo-speleothems, indicating
183 that the deposition of the paleo-speleothems has been quickly terminated by the low
184 temperature hydrothermal process. Given that the hydrothermal episode developed
185 after the beginning of the second transgression, chert lens (as siliceous tufa) should be
186 observed upon the karstic surface, nevertheless, siliceous cements and veins have been
187 strictly confined beneath the karstic surface. Thus we interpret the deposition and
188 hydrothermal silicification of the sheet-crack calcareous speleothems as successive
189 processes during exposure and karstification.

190 Modern karst studies indicate that necessary condition for karstic dissolution is the
191 soil-ecosystem (soil, plant, microbial, etc.), which afford organic matter and plentiful
192 CO₂^{37,38} in the water of an epikarst zone and hence the relative speleothems could

193 partly record the overlying ecosystem information. Karst dissolution in some high-
194 altitude and cold-climate regions occurs in the absence of soil ⁷, however, and so
195 obviously a temperature gradient caused by a huge altitude drop is needed to form
196 speleothems in these conditions. Paleo-karsts are defined as karsts developed largely or
197 entirely during past geological periods ³⁹. Freytet (2002) refers to karsts or vugs that
198 are centimeters to decimeters as microkarsts ¹¹, and these are an important evidence of
199 ancient subaerial exposure and paleosols formation ^{9,11,40}. Like pseudomicrokarsts ¹¹,
200 we define the microkarsts developed in past geological periods as paleomicrokarsts, in
201 which the speleothems are defined as paleomicrospeleothems. The Precambrian
202 palaeosols are habitats for early terrestrial life. The paleomicrospeleothems in the
203 corresponding carbonate strata are important geological evidence that record the early
204 biological evolution of the Earth. Paleomicrospeleothems (fibrous flowstone lining
205 grike system) found in the Mesoproterozoic in Canada ⁴¹ and U.S.A ³⁵ and the exquisite
206 paleomicrospeleothems (icicle-like pendants, hemispherical protrusions and ground-up
207 columns) reported in the Dengying Formation ⁴² may represent contemporaneous
208 pedogenesis processes. In the early Ediacaran, although recovery of ocean-ecosystem
209 from the brutal snowball Earth had been confirmed by vase-shaped fossils in tillite, the
210 geological evidence for terrestrial-ecosystem revival are still expected yet. Here, the
211 silicified paleomicrospeleothems preserved in the 3-5 m cap dolostone suggest that the
212 soil-ecosystem had been broadly established in South China just after uplifting and
213 exposing of the cap dolostone.

214 **4. Summary and Implication**

215 This paper reports the widely distributed miniature silicified paleospeleothems in
216 sheet-cracks in Marinoan cap dolostone from South China, which depict specific karstic
217 process of the cap dolostone during uplifting and exposure caused by isostatic rebound.
218 These are 1) miniature speleothem growth during karstification; 2) speleothem
219 termination and silicification by low-temperature fluid before the second transgression.

220 These paleo-speleothems have recorded the rapid recovery of the soil-ecosystem after
221 a snowball Earth during cap dolostone rebound and karstic dissolution, which is key
222 geological evidence for the 'green' Earth model.

223 The karstic dissolution surface may have been widely distributed on a global scale
224 at early Ediacaran, implying that the coincident silicified calcareous paleo-speleothems
225 are also global distributed. The silicification preservation process has destroyed some
226 original geochemical information such as carbon/oxygen isotopes, but the plentiful
227 organic-rich laminae are preserved. Thus, the bio-markers in these organic-rich laminae
228 are expected to further document the evolution of soil-ecosystem.

229 **Acknowledgements**

230 This research was supported by the National Nature Science Fund of China
231 (41802027, 41873058), Natural Science and Technology Fund of Guizhou Province,
232 China [JZ(2015)2009], and the incentive subsidy funds from the Guizhou Education
233 University in 2019 for projects of the Ministry of Science and Technology and the
234 National Natural Science Fund of China: Study on paleo-karst structure preserved in
235 cap dolostone of Doushantuo Formation in South China. We thank Ke Pang and
236 Chuanming Zhou for helpful discussions and Joshua Musir for English correction.

237 **Author Contributions**

238 T.L., G.Z., and T.G. designed the research. T.L., G.Z., and T.G. collected the
239 samples. G.Z and T.G. conducted experiments. G.Z., T.G., and T.L. developed the
240 interpretation and prepared the manuscript with contributions from M.Z.

241 **Methods**

242 Three sheet-crack samples (14XFH-1, 14XFH-3 and 14XFH-5) from Xiaofenghe
243 section (N30°48'54", E111°03'20"), Hubei Provinces, three sheet-crack samples
244 (14DPc1-1, 14DPc1-2 and 14DPc1-3) from Daping section (N28°59'01", E110°27'42"),
245 Hunan Provinces, four sheet-crack samples (16WH-1, 16WH-2, 16WH-3 and 16WH-

246 4) from Wenghui section (N27°49'55", E109°01'32") , Guizhou Provinces and four
247 samples (18BDS-2, 18BDS-4, 18BDS-7 and 18BDS-9) from Beidoushan section
248 (N27°01'40", E107°23'22"), Guizhou Provinces were collected from the cap dolostone
249 of the Doushantuo Formation in South China. Petrographic slices (100 µm and 200 µm
250 in thickness) and polished slabs of the sheet-crack samples were cut both perpendicular
251 and horizontal to bedding plane and investigated under transmitted light microscopy
252 (TLM), reflected light microscopy (RLM) and fluorescent light microscopy (FLM).

253

254 Reference

- 255 1 Kennedy, M., Droser, M., Mayer, L. M., Pevear, D. & Mrofka, D. Late Precambrian
256 oxygenation; inception of the clay mineral factory. *Science* **311**, 1446-1449 (2006).
- 257 2 Knauth, L. P. & Kennedy, M. J. The late Precambrian greening of the Earth. *Nature* **460**, 728
258 (2009).
- 259 3 Kump, L. R. Hypothesized link between Neoproterozoic greening of the land surface and the
260 establishment of an oxygen-rich atmosphere. *Proceedings of the National Academy of Sciences* **111**,
261 14062-14065 (2014).
- 262 4 Condon, D. *et al.* U-Pb ages from the neoproterozoic Doushantuo Formation, China. *Science*
263 **308**, 95-98, doi:10.1126/science.1107765 (2005).
- 264 5 Zhou, C., Yuan, X., Xiao, S., Chen, Z. & Hua, H. Ediacaran integrative stratigraphy and
265 timescale of China. *Science China Earth Sciences* **62**, 7-24, doi:10.1007/s11430-017-9216-2 (2019).
- 266 6 Baker, A., Barnes, W. L. & Smart, P. L. Speleothem luminescence intensity and spectral
267 characteristics: Signal calibration and a record of palaeovegetation change. *Chemical Geology* **130**, 65-
268 76, doi:https://doi.org/10.1016/0009-2541(96)00003-4 (1996).
- 269 7 Frisia, S. & Borsato, A. in *Developments in Sedimentology* Vol. 61 (eds A. M. Alonso-Zarza
270 & L. H. Tanner) 269-318 (Elsevier, 2010).
- 271 8 Dorr, H. & Munnich, K. O. Annual Variations of the 14C Content of Soil CO₂. *Radiocarbon*
272 **28**, 338-345 (1986).
- 273 9 Amodio, S., Barattolo, F. & Riding, R. Early Cretaceous dendritic shrub-like fabric in
274 karstified peritidal carbonates from southern Italy. *Sedimentary Geology* **373**, 134-146,
275 doi:10.1016/j.sedgeo.2018.06.001 (2018).
- 276 10 Qing, H. & Nimegeers, A. R. Lithofacies and depositional history of Midale carbonate-
277 evaporite cycles in a Mississippian ramp setting, Steelman-Bienfait area, southeastern Saskatchewan,
278 Canada. *Bulletin of Canadian Petroleum Geology* **56**, 209-234, doi:10.2113/gscpgbull.56.3.209 (2008).
- 279 11 Freytet, P. & Verrecchia, E. P. Lacustrine and palustrine carbonate petrography: an overview.
280 *Journal of Paleolimnology* **27**, 221-237, doi:10.1023/a:1014263722766 (2002).
- 281 12 Alvaro, J. J. & Clausen, S. Microbial crusts as indicators of stratigraphic diastems in the
282 Cambrian Breche a Micmacca, Atlas Mountains of Morocco. *Sedimentary Geology* **185**, 255-265,

283 doi:10.1016/j.sedgeo.2005.12.025 (2006).

284 13 Zhou, C., Bao, H., Peng, Y. & Yuan, X. Timing the deposition of ¹⁷O-depleted barite at the
285 aftermath of Nantuo glacial meltdown in South China. *Geology* **38**, 903-906 (2010).

286 14 Hoffman, P. F. & Macdonald, F. A. Sheet-crack cements and early regression in Marinoan
287 (635 Ma) cap dolostones: Regional benchmarks of vanishing ice-sheets? *Earth and Planetary Science*
288 *Letters* **300**, 374-384, doi:10.1016/j.epsl.2010.10.027 (2010).

289 15 Allen, P. A. & Hoffman, P. F. Extreme winds and waves in the aftermath of a Neoproterozoic
290 glaciation. *Nature* **433**, 123, doi:10.1038/nature03176 (2005).

291 16 Jiang, G., Kennedy, M. J., Christie-Blick, N., Wu, H. & Zhang, S. Stratigraphy, sedimentary
292 structures, and textures of the late Neoproterozoic Doushantuo cap carbonate in South China. *Journal of*
293 *Sedimentary Research* **76**, 978-995 (2006).

294 17 Zhou, C., Lang, X., Huyskens, M. H., Yin, Q.-Z. & Xiao, S. Calibrating the terminations of
295 Cryogenian global glaciations. *Geology* **47**, 251-254, doi:10.1130/g45719.1 (2019).

296 18 Condon, D. *et al.* U-Pb Ages from the Neoproterozoic Doushantuo Formation, China. *Science*
297 **308**, 95-98 (2005).

298 19 Zhou, G., Luo, T., Zhou, M., Xing, L. & Gan, T. A ubiquitous hydrothermal episode recorded
299 in the sheet-crack cements of a Marinoan cap dolostone of South China: Implication for the origin of the
300 extremely C-13-depleted calcite cement. *Journal of Asian Earth Sciences* **134**, 63-71,
301 doi:10.1016/j.jseaes.2016.11.007 (2017).

302 20 Fairchild, I. J. & Baker, A. *Speleothem science: from process to past environments*. Vol. 3
303 (John Wiley & Sons, 2012).

304 21 Gams, I. Contribution to morphometrics of stalagmite. *Proceedings of the 8th International*
305 *Congress of Speleology* **8**, 276-278 (1981).

306 22 Tan, M. *et al.* Applications of stalagmite laminae to paleoclimate reconstructions: Comparison
307 with dendrochronology/climatology. *Quaternary Science Reviews* **25**, 2103-2117,
308 doi:https://doi.org/10.1016/j.quascirev.2006.01.034 (2006).

309 23 Baker, A., Smart, P. L., Edwards, R. L. & Richards, D. A. ANNUAL GROWTH BANDING
310 IN A CAVE STALAGMITE. *Nature* **364**, 518-520, doi:10.1038/364518a0 (1993).

311 24 Tan, L. *et al.* Quantitative temperature reconstruction based on growth rate of annually-layered
312 stalagmite: a case study from central China. *Quaternary Science Reviews* **72**, 137-145,
313 doi:10.1016/j.quascirev.2013.04.022 (2013).

314 25 Railsback, L. B. *et al.* The timing, two-pulsed nature, and variable climatic expression of the
315 4.2 ka event: A review and new high-resolution stalagmite data from Namibia. *Quaternary Science*
316 *Reviews* **186**, 78-90, doi:https://doi.org/10.1016/j.quascirev.2018.02.015 (2018).

317 26 Dreybrodt, W. & Romanov, D. REGULAR STALAGMITES: THE THEORY BEHIND
318 THEIR SHAPE. *Acta Carsologica* **37**, 175-184 (2008).

319 27 Tan, L. *et al.* Quantitative temperature reconstruction based on growth rate of annually-layered
320 stalagmite: A case study from central China. *Quaternary Science Reviews* **72**, 137-145 (2013).

321 28 Baker, A., Smart, P. L., Edwards, R. L. & Richards, D. A. Annual growth banding in a cave
322 stalagmite. *Nature* **364**, 518-520 (1993).

323 29 Baker, A., Proctor, C. J. & Barnes, W. L. Stalagmite lamina doublets: a 1000 year record of
324 extreme winters in NW Scotland. *International Journal of Climatology* **22** (2002).

-
- 325 30 Wang, X. *et al.* PRELIMINARY ANALYSES BY SIMS ON TRACE COMPONENTS OF
326 STALAGMITE MICROLAYERS AND THEIR CLIMATE SIGNIFICANCE. *Quaternary* **19**, 59-
327 66,97-98 (1999).
- 328 31 Brook, G. A., Rafter, M. A., Railsback, L. B., Sheen, S. W. & Lundberg, J. A high-resolution
329 proxy record of rainfall and ENSO since AD 1550 from layering in stalagmites from Anjohibe Cave,
330 Madagascar. *Holocene* **9**, 695-705, doi:10.1191/095968399677907790 (1999).
- 331 32 Aubrecht, R., Brewercarias, C., Smida, B., Audy, M. & Kovacik, L. Anatomy of biologically
332 mediated opal speleothems in the World's largest sandstone cave: Cueva Charles Brewer, Chimantá
333 Plateau, Venezuela. *Sedimentary Geology* **203**, 181-195 (2008).
- 334 33 R, C., T, T. & Y, X. *Research on Sinian Strata with ore deposits in the Yangzi (Yangtze) region,*
335 *China.* (1989).
- 336 34 Wheeler, W. H. & Textoris, D. A. Triassic Limestone and Chert of Playa Origin in North
337 Carolina. *Journal of Sedimentary Research* **48**, 765-776 (1978).
- 338 35 Skotnicki, S. J. & Knauth, L. P. The Middle Proterozoic Mescal Paleokarst, Central Arizona,
339 U.S.A.: Karst Development, Silicification, and Cave Deposits. *Journal of Sedimentary Research* **77**,
340 1046-1062 (2007).
- 341 36 Cui, Y. *et al.* Germanium/silica ratio and rare earth element composition of silica-filling in
342 sheet cracks of the Doushantuo cap carbonates, South China: Constraining hydrothermal activity during
343 the Marinoan snowball Earth glaciation. *Precambrian Research*, 105407,
344 doi:https://doi.org/10.1016/j.precamres.2019.105407 (2019).
- 345 37 Blyth, A. J. *et al.* Molecular organic matter in speleothems and its potential as an
346 environmental proxy. *Quaternary Science Reviews* **27**, 905-921 (2008).
- 347 38 Kaufmann, G. Stalagmite growth and palaeo-climate: the numerical perspective. *Earth and*
348 *Planetary Science Letters* **214**, 251-266 (2003).
- 349 39 Bosak, P., Ford, D. C., Glazek, J. & Horacek, I. (Academia, Publishing House of the
350 Czechoslovak Academy of Sciences, Prague, Czechoslovakia, 1989).
- 351 40 Semeniuk, V., Percival, I. G. & Brocx, M. Subaerial disconformities, microkarst and paleosols
352 in Ordovician limestones at Bowan Park and Cliefden Caves, New South Wales, and their geoheritage
353 significance. *Australian Journal of Earth Sciences* **66**, 891-906, doi:10.1080/08120099.2019.1577297
354 (2019).
- 355 41 Kerans, C. & Donaldson, J. A. *Proterozoic Paleokarst Profile, Dismal Lakes Group, N.W.T.,*
356 *Canada 1.* (1988).
- 357 42 Ding, Y. *et al.* Cavity-filling dolomite speleothems and submarine cements in the Ediacaran
358 Dengying microbialites, South China: Responses to high-frequency sea-level fluctuations in an
359 'aragonite-dolomite sea'. *Sedimentology*, doi:10.1111/sed.12605 (2019).

360 **Figure Legends**

361 **Figure 1 | Polished slab and micrographs of stalactite from Beidoushan**
362 **section. a**, Polished slab shows stalactites in a sheet-crack scanning by a HP ScanJet,
363 the white solid rectangle highlights a column (connective bodies of stalactite and

364 stalagmite), white dotted rectangles highlight conjunction stalactites, the yellow arrow
365 denotes a single complete stalactite with “soda straw” drip channel. **b**, Petrographic slice
366 shows transverse and vertical sections of stalactite under TLM (transmission light
367 microscope), the white and red arrows denote the vertical and transverse sections of
368 “soda straw” drip channel, respectively. **c**, Enlarged view of the stalactite vertical
369 section in **b** (rectangle) under FLM (fluorescent light microscope), the white arrow
370 denotes the vertical section of “soda straw” drip channel. **d**, Enlarged view of stalactite
371 transverse in **b** (rectangle) under FLM, red arrows denote the transverse of “soda straw”
372 drip channel.

373

374 **Figure 2 | Polished slabs and micrographs of stalagmite, stalactite and coating**
375 **from Wenghui section. a**, Polished slab showing stalagmite, stalactite and coating in a
376 sheet-crack, white dotted lines highlight the coating areas in the sheet-crack, white
377 arrows denote stalactites, yellow arrows denote stalagmites. **b**, Petrographic slice shows
378 a vertical section of stalagmite and coating under RLM, white dotted lines highlight the
379 coating areas. **c**, Enlarged view of coating vertical section shows the organic-rich
380 laminae in **b** (rectangle) under FLM. **d**, Petrographic slice shows stalagmite and
381 stalactite transverses under TLM, red arrows and yellow arrows denote a single “soda
382 straw” drip channel and the aggregation of “soda straw” drip channel, respectively. **e**,
383 Enlarged view of a stalactite vertical section in **d** (rectangle) under FLM, showing the
384 organic-rich laminae and “soda straw” drip channel. **f**, Enlarged view of a stalagmite
385 transverse section in **d** (rectangle) under FLM, showing the organic laminae but lack of
386 “soda straw” drip channel.

387

388 **Figure 3 | Polished slab, hand specimen and micrographs of coatings and a**
389 **special stalactite. a**, Polished slab shows coatings in a sheet-crack, white arrows denote
390 the coating of a dolostone breccia. **b**, Hand specimen shows a coating lining in a sheet-
391 crack, white dotted line highlights the coating boundary, black and red arrow denote

392 botryoidal and mold structure of the coating. **c**, Petrographic slice shows a coating with
393 a vermiform-like helictite under FLM. **d**, Enlarged view of the helictite in **c** (rectangle)
394 under SEM (scanning electron microscope). **e**, Petrographic slice shows a partly
395 silicified organic-rich calcareous coating under TLM. **f**, Enlarged view of the coating
396 in **e** (rectangle) under SEM, showing the silicified calcareous coating, white arrows
397 highlight the siliceous cements. **g**, Enlarged view of the coating in **e** (rectangle) under
398 FLM, showing the organic-rich laminae. **h**, Petrographic slice shows a silicified
399 stalactite under TLM, white arrows highlight the residual calcite laminae. **a**, **c** and **d**
400 from Beidoushan section, **b** from Zhangcunping section, **e-g** from Daping section, **h**
401 from Xiaofenghe section.
402

Fig. 1

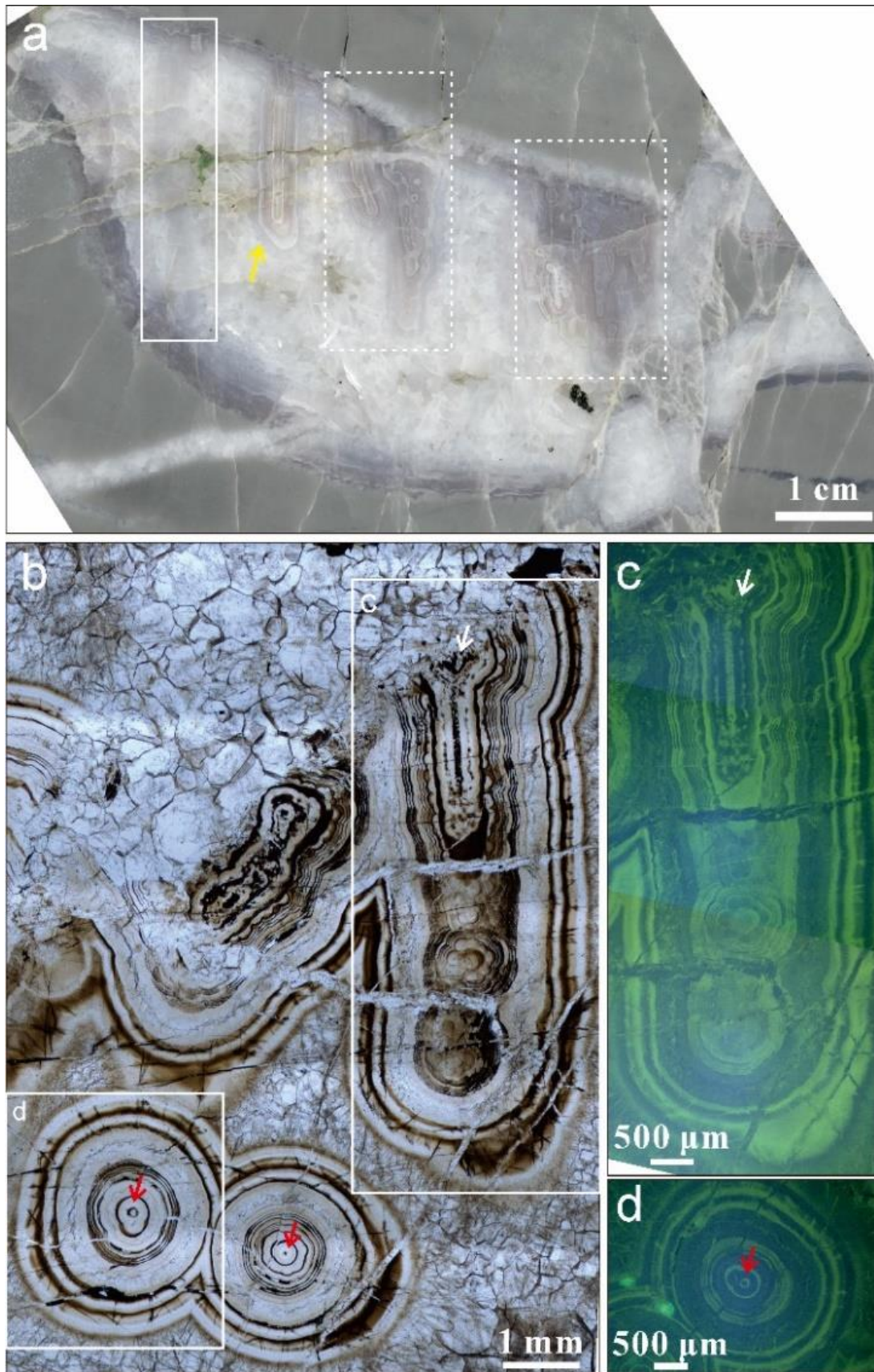


Fig. 2

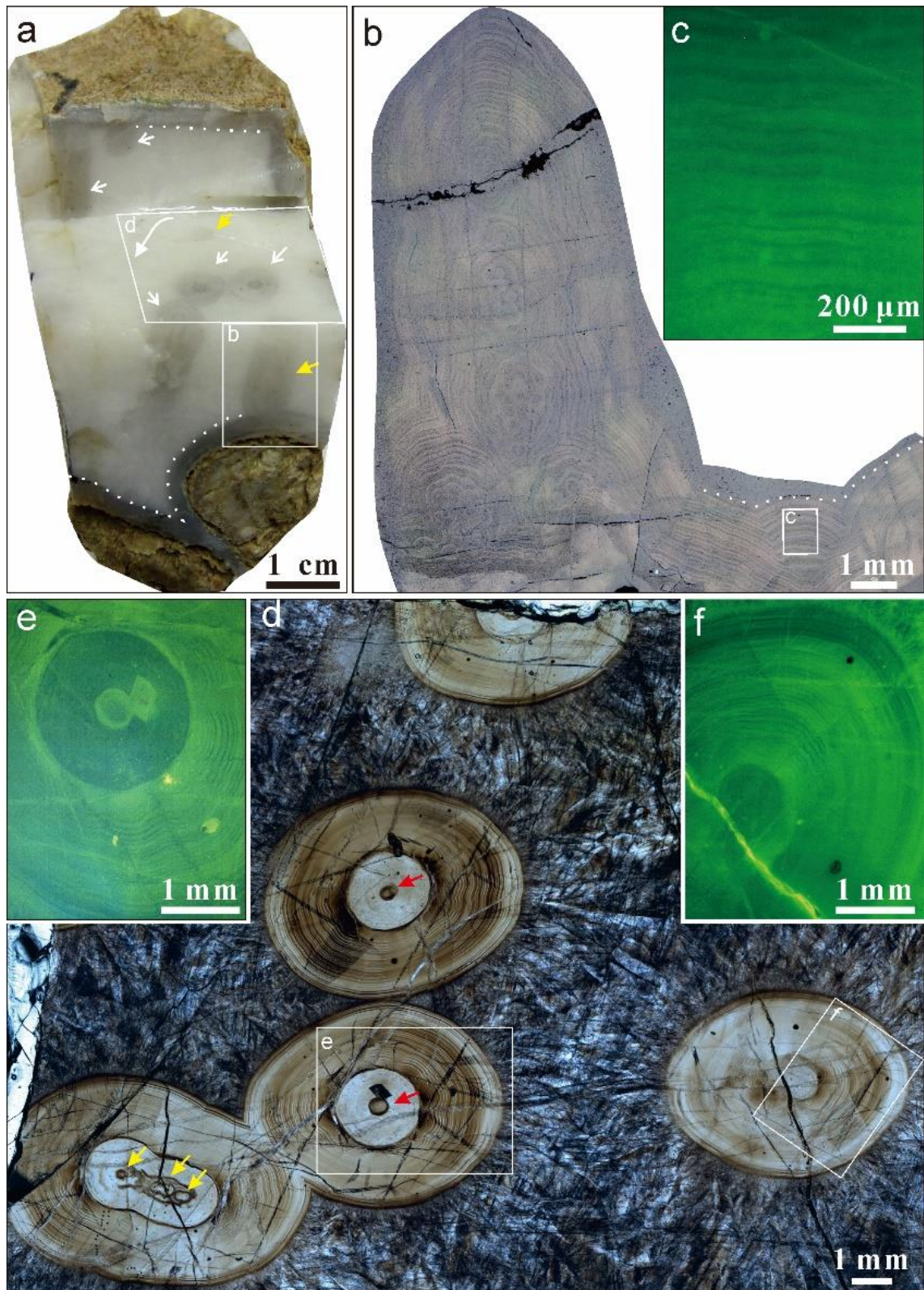


Fig. 3

