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1 **A Test of the Biogenicity Criteria Established for**
2 **Microfossils and Stromatolites on Quaternary Tufa and**
3 **Speleothem Materials Formed in the “Twilight Zone” at**
4 **Caerwys, U.K.**

5
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16

17 **Running title:** Biogenicity of tufa stromatolites

19 **Abstract**

20 The ability to distinguish the features of a chemical sedimentary rock that can
21 only be attributed to biology is a challenge relevant to both geobiology and
22 astrobiology. This study aimed to test criteria for recognizing petrographically the
23 biogenicity of microbially influenced fabrics and fossil microbes in complex
24 Quaternary stalactitic carbonate rocks from Caerwys, UK. We found that the
25 presence of carbonaceous microfossils, fabrics produced by the calcification of
26 microbial filaments, and the asymmetrical development of tufa fabrics due to the
27 more rapid growth of microbially influenced laminations could be recognized as
28 biogenic features. Petrographic evidence also indicated that the development of
29 "speleothem-like" laminae was related to episodes of growth interrupted by
30 intervals of non-deposition and erosion. The lack of any biogenic characteristics
31 in these laminae is consistent with their development as a result of variation in the
32 physico-chemical parameters that drive calcite precipitation from meteoric waters
33 in such environmental settings.

34 **Key words:** microfossil, stromatolite; biogenicity; carbonate; tufa; speleothem

35

36 **Introduction**

37 The ability to distinguish those features of a chemical sedimentary rock that can
38 only result from biology has proven to be a challenge for carbonate deposits (e.g.,
39 Wright and Barnett, 2015). As such an aim is essential for astrobiology and
40 geobiology research (e.g., Cady and Noffke, 2009), we tested the ability to
41 recognize signs of life and identify fossilized microbiota in Quaternary tufas and
42 speleothem materials with the use of biogenicity criteria developed to recognize
43 ancient microfossils (Sugitani et al., 2007; Wacey, 2009) and stromatolites (Buick
44 et al., 1981; Hofmann, 2000). Of particular relevance to life detection in
45 carbonates is the issue of a boundary that has been somewhat arbitrarily drawn
46 between “speleothem” terrestrial carbonate rocks that form in dark caves,
47 typically consisting of coarse columnar crystals that grow at rates of up to around
48 100 microns per year and are assumed to be essentially abiotic (e.g., Fairchild et
49 al., 2006; Frisia and Borsato, 2010), and spring and stream “tufa” carbonate rocks.
50 The latter are very similar to speleothem carbonate rocks, but they form in spring,
51 stream and lake settings where photosynthetic cyanobacteria, algae and plants
52 abound (e.g., Andrews and Brasier, 2005; Brasier et al., 2010) and are most
53 commonly comprised of small “micritic” calcite crystals. Unlike speleothems,
54 tufas are increasingly presumed to be biotically influenced (e.g., Freytet and
55 Verrecchia, 1998; Arp et al., 2001; Pedley, 2014). Tufas grow more rapidly than
56 speleothems, at rates of several millimeters to centimeters per year. There is

57 increasing recognition that tufa and speleothem systems form part of a continuum
58 that also includes hydrothermal “travertines” (Rogerson et al., 2014), which
59 suggests that some aspects of speleothem growth are likely to be enhanced by
60 microbial growth in some instances (Cacchio et al., 2004).

61

62 To test whether existing biogenicity criteria for microfossils and stromatolites
63 could distinguish biotic from abiotic features in chemical sedimentary
64 precipitates, we applied them to the potentially complex specimens that grow in
65 the so-called “twilight zone” at the entrance to modern caves (see Jones, 2010),
66 and in caverns of Quaternary tufa deposits. Carbonate rocks that formed in a
67 twilight zone where there is a transition from tufa to speleothem carbonate rocks
68 include the Holocene barrage tufa deposit located at Caerwys, north Wales, UK
69 (Figs. 1 and 2; Pedley, 1987). This tufa deposit contains several meter-scale
70 cavities or caverns that are locally decorated with speleothem-like stalactitic
71 calcite. The cavities are a primary feature that formed behind “curtains” of
72 petrified moss that draped over tufa dams known as “barrages” (Figs. 2 and 3).
73 We examined whether characteristics of the fabrics of specimens that formed in
74 these twilight zone conditions could be differentiated from those formed biotically
75 under the influence of photosynthesisers (“tufa-like”), and those formed
76 abiotically in the dark (“speleothem-like”). We also determined which

77 petrographic criteria developed for distinguishing biotic from abiotic precipitates
78 were most successful when applied to these Holocene specimens, with potential
79 implications for early Earth studies and astrobiology searches.

80

81 *Abiotic vs biotic origins of tufas and speleothems*

82 Calcite precipitation in streams where tufas form was, until recently, most
83 commonly viewed as a purely physico-chemical process (e.g., Zhang et al., 2001)
84 in which CO₂ outgasses from fluids causing them to become supersaturated with
85 respect to calcite, as reflected in the net thermodynamic equilibrium equation:

87 CO₂ gas enrichment in meteoric waters occurs where they filter through biogenic
88 CO₂-rich soil zones. The partial pressure of CO₂ builds in these environments so
89 modern soil zone pCO₂ commonly considerably exceeds that of atmospheric CO₂.
90 Calcite precipitation (Eq. 1) is typically associated with outgassing of this gas-rich
91 fluid at spring effluents and where such fluids flow over obstacles like boulders or
92 tree roots (e.g., Zhang et al., 2001). Recently this model has been challenged by
93 Hammer and co-authors (2010) who found that dissolved gas concentrations
94 decrease very little by turbulence caused by flow over surface irregularities,
95 which led them to conclude that the most important role of turbulence was to

96 increase precipitation rates by bringing solutes to and from the calcite surface
97 during turbulent mixing in the water column. Though the formation of stalactite
98 and stalagmite speleothems in caves has most commonly been attributed to
99 abiotic calcite precipitation driven by such physico-chemical processes (e.g.,
100 Frisia and Borsato, 2010), field studies (Freytet and Verrecchia, 1998; Vazquez-
101 Urbez et al., 2009; Glunk et al., 2011) and laboratory experiments with viable
102 biofilms collected from modern stream settings (Rogerson et al., 2008; Pedley et
103 al., 2009) have demonstrated that both abiotic and biotic processes influence
104 calcite precipitation in streams.

105 Recent experiments and field studies have also demonstrated that tufa
106 precipitation can be significantly enhanced, even driven, by microbial
107 extracellular polymeric substances (EPS) (e.g., Rogerson et al., 2008; Glunk et al.,
108 2011; Pedley et al., 2014). The EPS of non-viable organisms has also been
109 implicated in tufa formation (Rogerson et al., 2008). Biofilms of some species of
110 cyanobacteria are reportedly associated with their own specific microfabrics
111 (Freytet and Verrecchia, 1998), and such petrographic evidence would support the
112 hypothesis that some cyanobacteria exert direct control on tufa formation.

113

114 Diagenetic alteration following deposition adds further complexity to the ability
115 to determine the biogenicity of precipitated carbonate rocks like tufas and

116 speleothems. In spring or stream carbonate deposits, primary biofabrics may be
117 rapidly overprinted and recrystallized generating textures that appear abiotic
118 (Jones and Peng, 2012). For example, diagenetic changes transform primary tufas
119 from finely crystalline (micritic) to more coarsely crystalline (sparry) calcite, the
120 fabric changing either by aggrading neomorphism (Love and Chafetz, 1988;
121 Janssen et al., 1999) or simply continued growth of favored crystals (Brasier et
122 al., 2011). Yet characterizing all coarse, sparry calcite fabrics as either alteration
123 products or abiotic would be an over-simplification (Brasier et al., 2011) that
124 could lead to many microbial fossils, both ancient and modern, being overlooked.

125

126 **Materials**

127 *The Caerwys tufa*

128 The tufa deposit studied here was found to the south of the village of Caerwys in
129 north Wales, UK (Figs. 1 and 2). The waters that formed the tufa were sourced
130 from a spring in the Carboniferous limestone (Pedley, 1987). Tufa precipitation at
131 Caerwys has been constrained via radiocarbon techniques to the Holocene and
132 pre-Holocene ‘Late Glacial’ intervals (Preece and Turner, 1990). Deposition has
133 now ceased but a small analogous active site is found nearby at Ddol (Preece and
134 Turner, 1990). The Caerwys tufa forms a veneer of Quaternary terrestrial

135 carbonate rock over the underlying geology. It grew in a steep stream that flowed
136 down the scarp-face of a Carboniferous Limestone outcrop, with a series of
137 cascading pools developing behind arcuate tufa dams or “barrages” that were
138 oriented transverse to flow (Fig. 2; Pedley, 1987). The Caerwys system would
139 have resembled the currently active tufa-depositing stream at Alport, Derbyshire,
140 UK (Fig. 3). In both cases (Caerwys and Alport) unconsolidated micrite muds are
141 found in the pools between the barrages. Some of these pools contain isolated
142 decimeter-scale thrombolitic heads constructed by calcifying cyanobacteria, green
143 algae, and invertebrates. The barrage dams themselves comprise indurated but
144 vuggy carbonate walls that include a similar assemblage of fossil organisms.
145 Though extensively quarried, the internal fabric of the barrage system is visible
146 (Fig. 2) and preserved as a site of special scientific interest (SSSI).

147

148 Lithostratigraphy and mollusc biostratigraphy of the quarry were described by
149 Preece (1978; 1982) and a facies model was compiled by Pedley (1987). Tufa
150 oxygen and carbon isotopes were detailed and their Quaternary climate
151 implications discussed by Garnett et al. (2006). The latter estimated summer
152 water temperatures were in the range of 13 to 16.5 °C on the basis of tufa and
153 gastropod $\delta^{18}\text{O}$ values.

154

155 *Specimens exhibiting the continuum of tufas and speleothems*

156 Pedley (1990) described calcitic tubes of tufa formed by fringe cements that
157 encrusted larger plants (macrophytes). The samples analyzed in this study fit that
158 basic description and calcite encrustations of macrophytes are identified by their
159 morphology. Internally they have a central longitudinal cavity that may remain
160 open or may have been filled by clastic grains (commonly but not necessarily of
161 tufa carbonate) or calcite cement. They are differentiated from hollow abiotic
162 stalactites such as “soda straws” in that they contain preserved carbonaceous
163 matter or recognizable impressions of organisms that become encrusted when
164 mineralized. In swampy paludal marshes and pool margins, most plant stems
165 grow upwards and, when encrusted by carbonate, become stalagmite-like deposits
166 (Pedley, 1990). In barrage systems, however, many plants including bryophytes
167 live on the overhangs of the barrage (dam) front, their stems and branches
168 hanging downwards. This leads to pendant, stalactite-like calcite-encrusted
169 structures (Fig. 2). Externally these calcitic encrustations appear indistinguishable
170 from “speleothem” stalactites or stalagmites formed in caverns. Encrustations
171 may be <10 mm to several tens of centimeters in width, and range from a few
172 centimeters to meters in length. Such encrustations are common but under-
173 reported for modern karst settings. The oldest known examples may be the
174 pendant cavity-filling cements of the 2.75 Ga Fortescue Group, Australia, which
175 were interpreted as biogenic by Rasmussen et al. (2009).

176

177 **Methodology**

178 Eleven different tubular specimens from Caerwys, each several centimeters in
179 length, were collected. All were examined in hand specimen and using standard
180 petrographic microscopy techniques. Specimens were injected with blue resin,
181 and both longitudinal and transverse thin-sections were prepared and analyzed.
182 All rocks were found to be minimally or non-luminescent when viewed under UV
183 light. Cathodoluminescence (CL) microscopy revealed that none of the specimens
184 luminesced. Thin-sections were examined and photographed with the use of
185 polarized light microscopy. Carbonaceous filaments entombed in calcite were
186 distinguished from dark micritic calcite by partially dissolving the specimen with
187 acetic acid. Similar petrographic histories were elucidated from all eleven
188 specimens, such that we could select two representative specimens, labelled S3.2
189 and Caerwys 1, for detailed study.

190

191 **Results**

192 The descriptions of hand-specimen scale observations are followed by
193 microscopic observations for specimen S3.2, followed by the same for specimen
194 Caerwys 1. The terms micrite (crystals $<4\mu\text{m}$ diameter), microspar (4 to $10\mu\text{m}$

195 diameter), and spar ($>10\mu\text{m}$ diameter) are used to indicate crystal sizes and do not
196 reflect the origin of the grains.

197

198 *Specimen S3.2: Hand-specimen scale observations*

199 Specimen S3.2 is a downward-tapering stalactitic rock (Fig. 4) that was collected
200 as a float specimen that was found adjacent to the central barrage outcrop in the
201 quarry (Fig. 2b and 2c). Internally there is strong asymmetry, and at least six
202 separate components of the visible fabric of the sample, referred to here as Zones
203 1-6, were delineated (Fig 5).

204 Zone 1 is located in the central section of the porous tufa, which is permeated by
205 c. 50 to 100 μm diameter hollow tubes of calcite that form shrub-like growths
206 oriented downward at around 55 degrees from horizontal (Fig. 4b). From
207 examination of longitudinal and transverse sections it was possible to discern that
208 these growths formed via micritic calcite encrustation of a biological (likely
209 cyanobacterial) substratum. The asymmetrical nature of the sample, when viewed
210 in cross-section, is due to the more extensive outward growth of this primary
211 depositional fabric in one direction away from the point of initiation. Denser-
212 looking white patches of tufa, developed on one (likely the upstream) side of this
213 sample, cover an area around 3 mm across and a centimeter in length.

214 Zone 2 (Fig. 5) consists of micrite intergrown with dark brown sparry calcite fans,
215 with the latter being dominant. Each fan is around 1 to 3 mm across, and all fans
216 grew toward the outward edge of the specimen. This zone forms a band around 1
217 cm thick on one side of the specimen (the side toward which Zone 1 micrite
218 prograded), and is traceable continuously around the perimeter, though it narrows
219 to <1 mm thick on the opposite side of the sample.

220 Zone 3 in hand-specimen consists of a 1 to 2 mm thick light brown band that
221 envelops calcite of Zone 2, and is capped by a darker brown 1 mm thick band.
222 Internally these bands contain several very fine sub-mm thick cream colored
223 laminae. These bands are thicker where they developed below cm-scale
224 overhangs.

225 Zone 4 is recognizable in hand-specimen only as a white band that separates
226 brown calcite below it from very similar-looking brown calcite above, which is
227 designated as Zone 5. Note that Zone 4 appears brown in thin-section (Fig. 5).

228 Zone 6, the outer casing of the specimen, consists of a layer of cream colored
229 botryoidal calcite, around 2 mm thick on one side and 6 mm thick on the other.
230 This outer zone seems to be divided into two bands by a very thin dark lamina.

231

232 *Specimen S3.2: Microscopy*

233 Two thin-sections of sample S3.2 were made from the cut specimen. Scans of
234 these are shown in Figure 4, one from the transverse sawn section (S3.2A) and the
235 other from the longitudinal sawn section (S3.2B). Petrographic analysis of these
236 thin sections confirmed that Zone 1 comprises 6.5 to 26 μm (mostly c. 20 μm)
237 diameter dominantly sub-vertically oriented biological filaments that were
238 encrusted by 18 to 50 μm thick walls of calcite (Figs. 4, 5 and 6a). The
239 carbonaceous filaments themselves have mostly been oxidized, leaving behind
240 empty calcite tubes (Figs. 6a and 7a), though some tubes contain carbonaceous
241 material that resembles hollow and partially decomposed cyanobacterial
242 trichomes within a sheath (Figs. 7b and c). The central parts of each calcite tube
243 that would have been in contact with the carbonaceous filament are comprised of
244 an envelope of small microcrystalline crystals. The remaining outer part of each
245 calcite tube wall is constructed of radiating c. 20 μm diameter spar crystals (Fig.
246 7a). Also in Zone 1 is a cluster of hollow calcite tubes that ranged from 250 to
247 500 μm across (Fig. 7d). These each have an inner zone of microspar (crystals c.
248 20 μm diameter) followed by two rings of larger sparry crystals, each c. 45 μm
249 thick. Some of these tubes have sparry calcite fan growths on one side, which
250 marks the start of Zone 2.

251

252 The first Zone 2 sparry calcite fans (Figs. 4, 5 and 6a) nucleated directly on the
253 spar of Zone 1 encrusted tubes. These two spar types are, in some locations, in
254 optical continuity, which indicates that Zone 1 spar acted as a template for
255 precipitation and growth of Zone 2 spar. Some curved, dark micritic growth lines
256 within the fans are traceable between fans (Fig. 6a). Fans interfered with each
257 other where they touched during growth. Some fans terminated in smooth curved
258 surfaces; others were flat-topped (e.g. Fig. 8); and several exhibited pointed
259 euhedral crystal terminations. Growth of Zone 2 seemingly ceased for extended
260 periods of time (perhaps months?) on at least three occasions. These cessations
261 are marked by dark micritic layers from which new fans nucleated. The latter are
262 indicated by their different crystallographic orientations from the underlying fans
263 (Fig. 6a). A magnified view of one of the Zone 2 fans, shown in Fig. 8, reveals
264 that the carbonaceous filaments interpreted as entombed cyanobacteria are
265 dominantly but not exclusively oriented sub-parallel to the direction of crystal
266 growth. They are c. 2 μm wide and 40 μm long, distinctly narrower than the
267 carbonaceous filaments of Zone 1. These narrower filaments cross through some
268 of the finer, μm scale crystal growth bands within the fans (Fig. 8). The μm scale
269 growth bands were likely formed on approximately diurnal timescales (Andrews
270 and Brasier, 2005). Pedley (1987) suggested spar-entombed carbonaceous
271 filaments of the Caerwys quarry could be *Schizothrix* or *Phormidium* sp.
272 cyanobacterial fossils on the basis of growth form and diameter.

273

274 The contact between Zones 2 and 3 of this specimen (Figs. 4, 5, 6 and 9) is sharp
275 in places though more transitional in others due the optical continuity of
276 subsequent crystal growth. At its base, Zone 3 comprises numerous (at least six)
277 couplets of micrite and columnar sparite (Fig. 9b). A micrite band c. 5 μm thick
278 forms the nucleation region for numerous crystals of spar (mostly c.100 μm
279 diameter) in several locations in the specimen. Petrography revealed that several
280 of the latter columnar spar crystals, commonly with length to width ratios >6 ,
281 developed through competitive growth of crystals that nucleated in this band (e.g.,
282 Figs. 9c and 9d). Other columnar crystals stem from lower horizons that include
283 Zone 2 spar crystals (e.g., Fig. 9a). Inclusions in the columnar crystals appear as
284 bands oriented perpendicular to the direction of growth and parallel to (and
285 commonly in close proximity to) the bands of micrite (e.g., Fig. 9c and 9d). The
286 inclusions were identified primarily within the calcite crystals rather than between
287 them.

288 Most intriguing near the top of Zone 3 (Figs. 4, 5 and 10) is a patch a few mm
289 across that includes a series of circular to oval pores that range from 100 to 240
290 μm in diameter (Fig. 10). The latter are most easily interpreted as transverse
291 cross-sections of hollow tubes. One tube oriented longitudinally in the thin-
292 section extends for at least 2.2 mm. At higher magnification it was determined

293 that the walls of these tubes are thinly lined with dark micrite, surrounded by
294 cylinders comprised of spar crystals 100 to 400 μm in diameter (Fig. 10c and
295 10d). The latter are differently aligned from the columnar calcite host, radiating
296 outward from the tube center. The crystals aligned parallel to the direction of
297 growth of the columnar spar are elongated upward, forming flame-like growth
298 shapes. These crystals evidently grew contemporaneously and in competition with
299 the surrounding columnar spar.

300 Zone 4 was recognized petrographically by the re-appearance of micrite on one
301 side of the specimen (Fig 5b). This zone is laterally traceable into spar via two c.
302 5 μm thick sub-parallel micritic bands that mark its top and bottom. The micrite
303 comprises a porous network of peloids that includes hollow tubes of c. 130 μm
304 diameter.

305 Zone 5 spar crystals terminations range from pointed to flat or broken and are
306 delineated by inclusions (see Fig 5 and Fig. 11). In places they are draped in
307 continuous bands of dark, dust-like micrite that infilled the depressions and
308 smoothed out the topography (Fig. 11a). Most spar crystals terminate at these
309 micrite layers, though this was not always the case (Fig. 11b). For example, in one
310 place a fragment of micrite 340 μm across adhered to the specimen surface (Fig.
311 11) and sits flat on a micritic layer. Spar crystals nucleated on this detrital micrite
312 inclusion, though they were later out-competed by other columnar crystals.

313 Further, the protrusion formed by this blob of micrite clearly affected
314 development of the overlying layers (Fig. 11).

315 The tops of Zone 5 columnar crystals formed the substrate for Zone 6 crystal
316 growth. Zone 6 crystals (Fig. 5 and Fig. 12) are distinctly different from those of
317 Zone 5 and appear as networks of needle-like laths. The latter are arranged along
318 the faces of a crystal lattice (Figs. 12a and 12b). These laths are sub-crystals
319 (crystallites *sensu* Kendall and Broughton, 1978) that range individually in size up
320 to c. 1 mm long and 50 μm wide and that link to form larger millimeter-to-
321 centimeter scale composite crystals (Frisia and Borsato, 2010). These composite
322 crystals are sometimes in optical continuity with the Zone 5 columnar calcite on
323 which they grew (Fig. 12).

324

325 *Specimen Caerwys 1: Hand-specimen scale observations*

326 Caerwys 1 is an 8 cm long specimen that grew in a stalactitic fashion. It was
327 collected from a cavern within *in situ* barrage deposits located in the center of the
328 quarry. This specimen was collected from directly adjacent to the much larger
329 stalactitic rock shown in Fig. 2c. In longitudinal section it was possible to
330 recognize the sample has a highly porous center surrounded by several c. 0.5 to 1
331 mm thick layers that alternate with much thinner (c. 100 μm thick) lighter colored

332 layers (Fig. 13). At least three layers were traced in the specimen, though in
333 places the layers appear to be merged or truncated.

334

335 *Specimen Caerwys 1: Microscopy*

336 A thin-section of Caerwys 1 was stained with Alizarin Red S and Potassium
337 Ferricyanide. The pink color confirmed its non-ferroan calcite composition. The
338 central cavity (Fig. 13) of this specimen is highly porous, evidenced by the blue
339 resin (Fig. 14), and divided into several empty pockets by walls of sparry calcite.
340 One empty pocket is lined with 20 μm diameter microspar crystals (Fig. 14a) that
341 are partially intergrown and form a porous network. On both sides of this initial
342 cavity fill are crystal fans of sparry calcite, with crystal lengths of 80 to 150 μm .
343 Adjacent to the sparry calcite fans at the top of the specimen is a second empty
344 pocket, 3 mm across, that was progressively filled by 300 μm diameter sparry
345 calcite fans (Fig. 14b). These grew inwards from all sides toward the cavity
346 center. Dark-colored inclusions within some of these fans are oriented along
347 crystallite boundaries (Fig. 14c and 14d). The origin of these filamentous
348 microfossil-like inclusions is discussed further below. The bulk of the specimen is
349 comprised of layers of columnar sparry calcite that grew primarily outward as
350 fans (Fig. 14e-g). Each crystal is c. 500 μm long and 50 to 100 μm wide. These
351 sparry layers correspond to the thick, lighter colored layers observed in hand

specimen that are separated by laminae of micrite c. 130 μm thick (Fig. 13 and Fig. 14f). There is evidence that columnar sparry calcite fans were partially dissolved prior to or during deposition of the micrite layers (Fig. 14e), as some of the micrite layers are a little thicker (c. 230 μm) and more porous, particularly one layer close to the outside of the specimen (Fig. 14g).

Discussion

The criteria of Sugitani et al. (2007) and Wacey (2009) developed to establish the biogenicity of potential microbial fossils were applied to evaluate the biogenicity of the fossil-like objects in the two samples studied. For these specimens, their Quaternary age and sedimentary origins are not in doubt. These rocks have never been buried to any significant depth, so the characteristics of the precipitates and the fabrics were developed in the original sedimentary depositional environment.

Biotic vs abiotic growth of Specimen S3.2

A complex growth history of Specimen S3.2 was unravelled on the basis of the petrographic analysis, with different growth zones exhibiting different degrees of biotic influence. The oldest part of the specimen (in Zone 1; Figs. 5a and b) comprises dense, white colored calcitic tufa that contains clusters of hollow

371 carbonaceous tubes of fossilized cyanobacterial trichomes preserved inside
372 sheaths. Zone 1 was formed by calcification of filamentous cyanobacterial shrubs
373 that coated an overhanging leaf or twig. This photosynthesizing biofilm formed a
374 substrate for subsequent growth that was necessarily focused away from the tufa
375 wall toward the direction of light. Such biologically enhanced growth resulted in
376 the asymmetrical, elongated form of the specimen. A network of 250 to 500 μm
377 diameter hollow calcite tubes was formed by chironomid insect larvae, perhaps in
378 the late Spring season as waters warmed up (Janssen et al., 1999; Brasier et al.,
379 2011). Filamentous microbes coated these tubes, separated by at least one and
380 possibly two or three pauses of unknown duration (perhaps weeks or months,
381 likely at most a few years). Zones 1 and 2 are at least part contemporaneous, with
382 Zone 2 sparry calcite shrubs containing thinner entombed carbonaceous filaments
383 dominantly forming on the side of the specimen that received less light. Their
384 presence on the more illuminated side of the specimen toward the end of Zone 1
385 deposition, including in small crevices, is consistent with the onset of shaded,
386 lower light intensity conditions that supported the growth of microbial species
387 associated with spar formation.

388

389 The Zone 1 microfossils must have been syngenetic with the calcite deposition, as
390 the calcite initially developed as tubes nucleated on the filaments (Figs. 4, 5, 6a

391 and 7). It is possible that the Zone 2 microfossils (Fig. 8) represent endoliths that
392 bored into the tufa post-deposition, as they are oriented parallel to crystal growth
393 planes and cut across the micron-scale growth lines within the sparry calcite
394 crystal fans, features previously used as indicative of an endolithic habit (Knoll et
395 al., 2013). However the filaments in the Caerwys samples protrude across laminae
396 that likely formed on diurnal timescales, well within the lifetime of entombed
397 individual microorganisms. Further, endolithic organisms would also be expected
398 to target earlier formed tufa micrite as well as the crystal fans. The occurrence of
399 the Zone 2 filaments close to the center of the specimen and not in the outer parts
400 makes it unlikely that the cyanobacterial filaments preserved in Zone 2 were
401 endoliths. More likely, and as Pedley (1987) inferred, the filaments were
402 fossilized by syn-depositional calcite entombment.

403

404 Evidence for microbial influence on the growth of Zones 1 and 2, consistent with
405 the microfossil biogenicity criteria of Wacey (2009), includes:

- 406 1) Two different populations of carbonaceous filaments, each community
407 associated with its own characteristic carbonate rock microfacies and not
408 randomly distributed.
- 409 2) Entombed clusters of hollow brown-colored carbonaceous filaments that
410 are syngenetic with the carbonate rock. These microfossils include

411 sheathed trichomes and are comparable in size and morphology with
412 extant cyanobacteria.

413 3) Calcitic molds of colonies of microbial filaments preserved in the
414 carbonate rock, with calcification specifically on and around the filaments,
415 consistent with microbial influence on crystal nucleation.

416 Zone 3 (Fig. 9) lacks the microfossils of Zones 1 and 2 (Figs. 6, 7 and 8). The
417 thicker layering on the undersides of overhangs (Fig. 4b, 5b) is consistent with a
418 dominantly abiotic growth process. However, as in Zone 1, the 100 to 240 μm
419 diameter tubes (Fig. 10) are best interpreted as chironomid larval tubes (e.g.,
420 Brasier et al., 2011). Chironomid larvae are detrital feeders, which implies that
421 Zone 3 formed in detritus-rich flowing stream water. Tubes at the top of Zone 3
422 could be directly associated with the micrite of Zone 4. This inference is based on
423 the micritic peloids that could be of fecal origin, and additional tubes of likely
424 chironomid origin that occur in the Zone 4 micrite. This suggests that Zone 3 spar
425 and Zone 4 micrite are partly contemporaneous, and indeed Zone 4 micrite
426 merges laterally into sparry calcite.

427 Petrographic evidence that Zone 5 columnar spar is primary and not the result of
428 recrystallization includes the aggradational fabrics that surround the micrite
429 inclusion (Fig. 11). That the micrite inclusion sits flat on a thin micritic layer (Fig.
430 11a) is consistent with the latter representing a phase (perhaps a dry summer)

431 during which little calcite crystal growth occurred. New columnar crystals
432 nucleated on top of the micrite (Fig. 11b), presumably during a wetter phase. The
433 resulting topography caused deflection of the subsequent growth laminae.
434 Ultimately the spar that nucleated on top of the micrite inclusion was out
435 competed by the surrounding larger columnar crystals (Fig. 11b). Columnar spar
436 of Zone 5 likely formed within or in very close proximity to the active tufa-
437 depositing stream. These conditions could have been found behind the
438 downstream facing accretionary surface of an actively accumulating tufa barrage.
439 No obvious indicators of a biogenic cause for calcite deposition were identified in
440 Zone 5. This does not necessarily imply that nucleation of Zone 5 spar was
441 wholly abiotic: extracellular polymeric substances produced by microbes were
442 very likely present in the stream water, though there was no direct evidence that
443 they contributed to the formation of Zone 5 spar.

444 Similar to the crystals of the Zone 5 spar, the crystals of Zone 6 also lacked
445 carbonaceous microfossils (Fig. 12). The fabric of Zone 6 was reminiscent of the
446 open dendritic speleothem texture described by Frisia and Borsato (2010). Such
447 textures are known to form at cave entrances, in places subject to kinetic
448 processes such as prolonged degassing phenomena. Such a scenario is consistent
449 with Zone 6 developing as a late-stage cave speleothem-like meteoric growth
450 within the cavern. Unlike the within-stream conditions that supported the growth

451 of Zones 1-5, Zone 6 developed when the tufa stream system itself had become
452 inactive.

453 In short, petrographic observations revealed that Zones 1 and 2 formed in the
454 presence of microbes that included cyanobacteria; Zone 3 calcite growth was
455 dominantly abiotic except for calcite tubes most likely constructed by chironomid
456 larvae; Zone 4 is attributed to chironomid larvae that consumed microbes; there
457 are no obvious preserved indicators of biological activity or control on calcite
458 precipitation in Zone 5 and Zone 6, and the latter formed in different
459 environmental circumstances compared to those that supported the growth of
460 Zones 1 – 5. Abundant petrographic evidence for syn-depositional growth of
461 columnar calcite spar is found in places with entombed cyanobacterial filaments
462 (Zone 2), where crystal growth continued behind the aggrading outer surface layer
463 (Fig. 6); where there is evidence of micrite bands capping spar layers, and
464 competitive crystal growth of spar crystals (Fig. 9); where insect larval tubes are
465 found in sparry calcite layers (Fig. 10); and where detrital micrite stuck to the
466 specimen surface and interfered with growth of overlying spar crystals (Fig. 11).
467 There is no evidence for recrystallization that would have required dissolution.
468 Despite the presence of cyanobacteria in Zones 1 and 2, the most clearly
469 laminated (i.e. “stromatolitic”) zones are 3 and 5 (Figs. 4 and 5). The latter are the
470 most cave speleothem-like and arguably abiotic sections. This lamination is
471 discussed further below.

472

473 *Biotic vs abiotic character of Specimen Caerwys 1*

474 Specimen Caerwys 1 is similar to specimen S3.2 in that it was nucleated on a
475 downward hanging biological substrate, overgrown by successive layers of sparry
476 calcite that extend to the outside of the sample. Caerwys 1 is a thinner specimen
477 than S3.2. This may be partly due to absence of prograding cyanobacterial
478 filaments in the core of Caerwys 1. Rather, the initial biological substrate seems
479 to have been a stem or branch of a larger plant. The predominantly sparry calcite
480 walls of Caerwys 1 are similar to Zone 2 of S3.2 (compare Figs 6b and 8 with Fig.
481 14c-f). Clusters of potential microfossil filaments in Zone 2 of specimen S3.2
482 (Fig. 8) and in the sparry calcite fans of Caerwys 1 (Fig. 14c) also share similar
483 properties of size, coloring and orientation parallel to the direction of crystal
484 growth. However, the orientation of the dark-colored Caerwys 1 filaments was
485 directly related to the orientation of the crystal structure. A comparison of the
486 observations against the biogenicity criteria of Sugitani et al. (2007) and Wacey
487 (2009) indicate that the Caerwys 1 filaments are much less convincing as
488 microfossil candidates than those found in the S3.2 sample.

489

490 *Biogenicity of the lamination?*

491 The specimens described here are layered carbonate rocks that by some
492 definitions could be identified as “tufa stromatolites” (Riding, 1991) or simply
493 stromatolites (e.g., Semikhatov et al., 1979). Therefore, to evaluate whether the
494 Caerwys tufa layering would be identified as biogenic when commonly used
495 stromatolite biogenicity criteria are applied, we used the criteria of Buick et al.
496 (1981) and Hofmann (2000) as critiqued in McLoughlin et al. (2013).

497 The first group of biogenicity criteria pertain to the context of the lamination and
498 include, for example, requirements that the structures be found in sedimentary or
499 metasedimentary rocks and be syn-sedimentary with the deposit in which they are
500 found. This is undoubtedly the case for these Quaternary tufas. Similarly, there is
501 a criterion that brecciated mat chips should be found accumulated in depressions
502 between convexly laminated mounds. Eroded chips of layered carbonate are
503 found within the pool facies at Caerwys (Pedley, 1987). Such findings establish
504 that the layered carbonate rocks are a primary sedimentary feature, but these
505 contextual criteria do not differentiate biogenic from abiotic stromatolites.

506

507 The second group of biogenicity criteria pertain to the morphology of the
508 lamination: a biogenic stromatolite should exhibit a preponderance of convex-
509 upward structures; contain laminae that thicken over the crests of flexures; consist
510 of laminations that are wavy, crinkled or have several orders of curvature; and

511 may be associated with thin, rolled-up fragments with coherent flexible laminae
512 that can reasonably be interpreted as microbial mats. However, none of these
513 criteria is itself diagnostic of a biogenic rock. Here we highlight, for example, that
514 several tufa stromatolites of cyanobacterial origin exhibit isopachous layering
515 (e.g., Janssen et al., 1999; Andrews and Brasier, 2005; Brasier et al., 2010; 2011).
516 Spar layers in Caeryws tufa specimen S3.2 Zone 3 that might otherwise be
517 interpreted as abiotic thicken over the crests of flexures, as do spar layers of Zone
518 5 (Fig. 11). Laminae of specimen Caerwys 1 seem thickest at the downward
519 pointing tip of the specimen (Fig. 13), which is consistent with the effects of
520 gravity and hence abiotic growth. Likewise, the thin micritic layers of Caerwys 1
521 are crinkled and curved (Fig. 13) yet the petrographic observations suggest that
522 these micrite bands are related to periods of exposure or non-deposition, as they
523 cap spar fans that are partially dissolved or eroded (Fig. 14e). Despite being
524 crinkled these micrite laminae are unlikely to be biogenic.

525

526 The third group of biogenicity criteria are those that relate to the nature of
527 microfossils and trace fossils within the lamination. Zones 1 and 2 of Specimen
528 S3.2 exhibit both entombed hollow carbonaceous filaments and calcitic external
529 molds of filaments oriented perpendicular to the lamination, not parallel to it.
530 Trace fossils of insect larvae are present within Specimen S3.2 Zone 3. It is

531 possible that these larvae were farming particular species of cyanobacteria above
532 their tubes, and that the cyanobacteria influenced crystal growth. Alternatively the
533 larvae might have produced their own growth-influencing organic substances
534 (Brasier et al., 2011). However there is no evidence for microbes directly causing
535 the lamination of Zone 3. Microfossils are notably absent in the most distinctly
536 laminated section, Zone 5.

537 Additional biogenicity criteria require that changes in the composition of
538 microfossil assemblages should be accompanied by morphological changes in
539 biogenic stromatolites. Where more than one microfossil assemblage is present in
540 the samples studied, changes in micromorphology were found in these specimens.
541 For example, the narrow filaments of Specimen S3.2 Zone 2 are associated with
542 sparry calcite fans (Fig. 8) whereas broader filaments in trichomes of Zone 1 are
543 found in sub-vertically hanging tubes of calcite (Figs. 4, 5, 6 and 7).

544 The entombed microorganisms of Specimen S3.2 are also organized and clustered
545 in a fashion consistent with colonial photoautotrophic growth. We infer that their
546 EPS did not simply bind sediment (e.g., Gerbersdorf and Wieprecht, 2014) but
547 that it actively assisted calcite crystal nucleation (Rogerson et al., 2008; Glunk et
548 al., 2011). This hypothesis is supported by the petrographic evidence for
549 preferential growth of the carbonate rock toward the most light-illuminated
550 direction. Insect larval tubes present in the Caerwys tufa (Fig. 10) would

551 potentially meet a criterion that biogenic stromatolitic fossils must be organized in
552 a manner that indicates trapping, binding or precipitation of sediment, though
553 whether the insect larvae actively trapped, bound or precipitated the sediment
554 themselves (e.g., Brasier et al., 2011) could not be discerned petrographically.

555

556 Though all of above criteria establish that the lamination is sedimentary in origin
557 (Fig.6a) and the cyanobacterial microfossils are consistent with evidence for
558 photoautotroph-induced specimen growth (see supplementary information S?), the
559 cause of most of the lamination in the Caeryws specimens is related to alternating
560 episodes of specimen growth, non-deposition and erosion (e.g., Figs. 9d, 11 and
561 14d). Physico-chemical parameters such as stream flow rates, pH, alkalinity,
562 saturation and temperature likely controlled the development of such lamination.
563 Though microbially produced EPS may have exerted some influence on the
564 laminae microstructure, direct evidence for microbial control on the lamination
565 was absent.

566 In summary, the criteria consistent with biogenic features in the layered tufas at
567 Caerwys are those that relate to fossils of the organisms themselves, and not
568 those of the lamination. Without the presence of microbial fossils, it would not be
569 possible to identify the biogenicity of the laminae. Layering alone is not

570 diagnostic of a biogenic structure in specimens like those characterized in this
571 study.

572

573 **Implications for astrobiology**

574 Carbonate rocks that may be targets in the search for martian microfossils were
575 identified by Niles et al. (2013). As with Earth's deep time stromatolites
576 (McLoughlin et al., 2013), discriminating purely abiotic chemical sedimentary
577 precipitates from biogenic rock structures of Mars will prove challenging. It is
578 encouraging that simple criteria devised for ancient stromatolites and microfossils
579 (Buick et al., 1981; Hofmann, 2000; Sugitani et al., 2007; Wacey, 2009) here
580 enabled biogenic microfossils to be distinguished from abiogenic pseudofossils in
581 a complex terrestrial case.

582 It is worth noting that recognition of microfossils requires detailed microscopic
583 examination: definitively identifying biogenic structures in the examined
584 Caerwys specimens would not have been possible at the outcrop or hand-
585 specimen scales. Robotic exploration of Mars has already located potentially
586 habitable streams (Grotzinger et al., 2014), structures consistent macroscopically
587 with microbially-induced sedimentary structures have been described (Noffke,
588 2015), and chemical signals consistent with martian life (Webster et al., 2015)

589 have been reported. Potential lessons from the Caeryws quarry, however, are that
590 the microbial structures visible under the microscope are not readily identifiable
591 as biogenic at the hand-specimen scale, and the nature of the laminations were
592 such that they could not be proven as biogenic at the hand-specimen or
593 petrographic microscope scales.

594

595 **Conclusions**

596 The microfossils found in specimen S3.2 display at the petrographic scale the
597 most convincing evidence for biogenicity: the layered stalactitic rock developed
598 as a result of the calcification of filamentous cyanobacteria and different
599 populations of carbonaceous filaments were each associated with their own
600 characteristic carbonate rock microfacies.. The entombed clusters of hollow
601 filamentous carbonaceous microfossils that included sheathed cyanobacterial
602 trichomes demonstrated that the microfossil evidence is syngenetic with the
603 carbonate rock. The influence of biology on the morphology of the deposit was
604 identified by the strong asymmetry of the sample fabric: preferential growth on
605 the most highly illuminated side of the barrage was associated with the presence
606 of photoautotrophic microbes preserved as colonies of calcitic filament molds.
607 Though some calcite spar fans in this sample formed in association with microbial
608 filaments, the columnar spar that formed during a latter growth stage toward the

609 outside of specimen S3.2 does not include entombed microfossils. In contrast to
610 specimen S3.2, the filaments found in the specimen Caerwys 1 were associated
611 with the crystal structure of the deposit, which according to the criteria of Sugitani
612 et al. (2007) and Wacey (2009), indicate that these structures are less plausible
613 microfossil candidates than those found in S3.2.

614

615 Petrographic evidence indicates that columnar spar is a primary fabric, and not
616 due to secondary crystal growth. This spar lacks obvious microfossils and formed
617 within the calcite-precipitating stream, but in poorly illuminated locations behind
618 the barrage front. Lamination is related to episodes of growth interrupted by
619 intervals of non-deposition and erosion. We interpret the petrographic evidence as
620 indicative of lamination formation controlled by physico-chemical parameters.
621 Interestingly, we found that lamination in the samples studied was not an
622 indicator of stromatolite biogenicity.

623

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632

633 **Author Disclosure Statement**

634 No competing interests exist.

635

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762

763 **Figure captions**

764

765 **FIG. 1:** Map showing the location of the Caerwys tufa in the UK. Inset map

766 shows the UK, with Wales labelled and Caerwys as a red dot. The larger map

767 shows the location of the Caerwys tufa quarry (red), and its relationship to
768 surrounding Quaternary alluvial sediments (orange) and underlying geology.
769 Carboniferous limestone (blue) supplies the calcium and bicarbonate ions to
770 groundwaters. These precipitate tufa calcite on emergence at springs associated
771 with the contact between the limestone and underlying Silurian siliciclastic rocks
772 (grey). Scale bar is 2km.

773

774

775 **FIG. 2:** Caerwys tufa quarry photographs **(a)** Unconsolidated micritic pool
 776 deposits on the right side of the image, adjacent to consolidated barrage facies
 777 (arrow points to the base of the barrage). The tufa barrage prograded downstream
 778 (towards the left). Isolated thrombolitic heads are found in the pool facies. **(b)**
 779 Block of the main tufa barrage preserved in the quarry center. People for scale are
 780 c.1.75m tall. **(c)** Stalactitic carbonate rocks that grew in a cavity of the same

781 barrage block shown in (b). Specimen Caerwys 1 is from this location, and S3.2
782 was found as a float specimen nearby. Lens cap for scale is 5.5 cm diameter.

783

784

785 **FIG. 3:** Active tufa stream at Alport, Derbyshire, UK, as an analogue for the
786 Quaternary Caerwys tufa. **(a)** View showing pool environment behind a barrage
787 (to the right of this image), with a thrombolitic head (see arrow). The white water
788 upstream is flowing over a barrage. **(b)** Close-up of a barrage, showing microbial

789 biofilm plus some green algae and bryophytes living subaqueously on the barrage
790 front, hanging down into the fast flowing stream. A cavity is developing behind
791 this calcifying structure sometimes referred to as a curtain. In larger barrages,
792 meter-scale caverns form behind the curtain (e.g., fig. 2c).

793

794 **FIG. 4:** Scans of thin-sections of specimen S3.2. (a) transverse cut, and (b)
 795 longitudinal cut. Blue color is from resin injected to show porosity.

796

797 **FIG. 5:** Interpreted scans of thin-sections of specimen S3.2. (a) transverse cut and
 798 (b) longitudinal cut. Interpreted boundaries between growth zones are shown as
 799 black lines, and the position from which growth initiated is shown as a red line.

800 Zones 1-6 are described in the text. Unlike wholly abiotic stalactites, this
801 specimen is strongly asymmetrical, caused by calcifying cyanobacteria favoring
802 the illuminated side of the specimen. Images are shown at the same scale.

803
804 **FIG. 6:** Micrographs of Specimen S3.2 thin-section A (transverse cut). (a) shows
805 Zone 1 (base, hollow calcite tubes that formed around downward-hanging

806 cyanobacterial filaments; example arrowed), Zone 2 (center, sparry calcite fans
 807 interlayered with micritic bands) and Zone 3 (top, columnar calcite crystals).
 808 Numbered squares refer to these zones. Green arrows point to cessations in
 809 growth, marked by dark micritic layers, from which new fans nucleated. White
 810 box in Zone 2 shows location of (b), which is a sparry calcite fan that contains
 811 entombed cyanobacterial filaments (arrowed).

812

813

814 **FIG. 7:** Micrographs of Specimen S3.2 showing biological fabrics. (a) Cross-
 815 polarized light image of Zone 1 calcite tubes formed around downward-hanging
 816 cyanobacterial filaments (transverse cut). Blue is resin, and black is holes in the

817 thin-section. **(b)** Plane polarized light image of calcite tubes containing
818 microfossils of filamentous cyanobacteria (longitudinal cut). Trichome in a sheath
819 is arrowed. **(c)** Higher magnification plane polarized light image of the trichome
820 and sheath shown in (b). **(d)** Plane polarized light image of a network of larger
821 diameter calcite-cemented holes best interpreted as insect (interpreted as
822 chironomid?) larval tubes.

823
824 **FIG. 8:** A sparry calcite fan containing entombed cyanobacterial filaments of
825 specimen S3.2 Zone 2. Note the filaments are dominantly oriented parallel to the
826 direction of crystal growth. However they also curve and cross each other, and are
827 not artifacts related to the crystal structure. Filaments also cross dark colored

828 growth banding (likely formed on ~diurnal timescales) in the crystal. Scale bar is
829 0.1 mm across.

830
831 **FIG. 9:** Sparry calcite of Specimen 3.2 Zone 3. **(a)** shows the top of Zone 2,
832 transitioning into Zone 3. Note the shrub-like calcite crystal fans with entombed
833 cyanobacterial filaments of Zone 2. **(b)** shows alternating laminae of calcite spar
834 and micrite of Zone 3. The arrow points to a partially broken pointed termination
835 of a spar crystal draped in dark micrite. **(c)** shows (apparently abiotic) sparry
836 calcite laminae found further from the specimen center than (b), with dusty
837 lamination caused by inclusions. **(d)** is the same area as (c), with polars crossed.
838 Note competitive growth has favored some crystals over others, resulting in a

839 columnar fabric. Examples of crystals that were out-competed are arrowed. Note
 840 also that new crystals nucleated on the micrite layers (presumed hiatuses in
 841 growth), consistent with this columnar spar being a primary fabric.

842 **FIG. 10:** Insect (likely chironomid) larval tubes in Specimen S3.2 Zone 3 spar.
 843 These are seen as evidence that the spar is primary and not recrystallized from
 844 micrite. (a) plane polarized light image, showing hollow tube (filled with blue
 845 resin) within the spar of Zone 3. (b) Same area as (a), with polars crossed. Note
 846 the influence of the insect larvae on crystal orientations. (c) Close up of some of
 847 the tubes in plane polarized light. (d) Same area as (c), with polars crossed. Some
 848 crystal orientations seem consistent with the broader columnar fabric of Zone 3.
 849

850 Crystals with different orientations might have been detrital grains assimilated by
851 the larvae for tube construction.

852

853

854 **FIG. 11:** Caerwys specimen 3.2 Zone 5 in thin-section. **(a)** Plane polarized light
855 image, showing sparry crystals (light) with dark micritic growth laminae. Arrow
856 points to a micritic grain that stuck to the specimen surface during growth, and
857 became enveloped in (primary) columnar spar. **(b)** Same area as (a) with polars
858 crossed. Note the influence of the detrital micrite clast (lower arrow) on columnar
859 spar growth. Crystals nucleated on the micrite were out-competed by the larger
860 columnar crystals (top arrow). This suggests the columnar spar was primary,
861 despite the fact that these large crystals cut through the dusty growth lamination.
862

863

864 **FIG. 12:** Caerwys specimen 3.2 Zone 6 in thin-section. **(a)** Plane polarized light
 865 image showing a mound of crystal laths nucleated on a flat surface (the top of a
 866 Zone 5 columnar calcite crystal, at the base of the image). **(b)** Close up of
 867 network of lath-shaped crystallites in plane polarized light. **(c)** Image with polars
 868 crossed, showing the network of lath-shaped crystallites forms composite crystals
 869 of Zone 6. All scale bars are 1 mm.

870

871

872 **FIG. 13:** Stalactitic specimen Caerwys 1 (longitudinally cut hand-specimen). The
873 central cavity formed around a downward-hanging twig. Alternating micritic
874 laminae (white) and sparry calcite fans (darker and thicker) grew on the outside.

875 Ruler for scale (larger divisions are centimeters, smaller divisions are
876 millimeters).

877

878

879 **FIG. 14:** Photomicrographs of Caerwys 1 thin-section. **(a)** The central cavity
880 region is highly porous, with several hollow, empty pockets (blue resin). The
881 empty pocket in (a) is lined with 20µm diameter microspar crystals. These grew
882 on peloidal micrite (arrowed). **(b)** A second empty pocket in the central zone, 3
883 mm across, that has been progressively filled by 300 µm diameter sparry calcite
884 fans. **(c)** Inclusions within these fans (arrowed), oriented along crystallite
885 boundaries. Their alignment and form suggest they are not cyanobacterial and
886 possibly not even microbial filaments. **(d)** Same crystal fan as shown in (c), with
887 polars crossed. **(e)** Layers of columnar sparry calcite growing dominantly outward
888 as fans that form the bulk of the specimen. There is evidence that columnar sparry
889 calcite fans were partially dissolved prior to or during deposition of the micrite
890 layers. **(f)** Close-up of one of the micritic laminae (dark band) between sparry
891 calcite fans. **(g)** Sparry calcite fans on the left, capped by a thick micrite layer
892 (dark band on the right) close to the outside of the specimen. All images taken in
893 plane polarized light except (d). Scale bars in (a), (e), and (g) are 0.5mm; scale
894 bars in other images are 0.1 mm.