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The Ediacaran period witnessed transformational change across the Earth–life system, but life on land during this interval is poorly understood. Non-marine/transitional Ediacaran sediments preserve a variety of probable microbially induced sedimentary structures and fossil matgrounds, and the ecology, biogeochemistry and sedimentological impacts of the organisms responsible are now ripe for investigation. Here, we report well preserved fossils from emergent siliciclastic depositional environments in the Ediacaran of Newfoundland, Canada. These include exquisite, mouldically preserved microbial mats with desiccation cracks and flip-overs, abundant Arumberia-type fossils and, most notably, assemblages of centimetre-to-metre-scale, subparallel, branching, overlapping, gently curving ribbon-like features preserved by aluminosilicate and phosphate minerals, with associated filamentous microfossils. We present morphological, petrographic and taphonomic evidence that the ribbons are best interpreted as fossilised current-induced biofilm streamers, the earliest

record of an important mode of life (macroscopic streamer formation) for terrestrial microbial ecosystems today. Their presence shows that late Ediacaran terrestrial environments could produce substantial biomass, and supports recent interpretations of Arumberia as a current-influenced microbial mat fossil, which we here suggest existed on a "streamer–arumberiamorph spectrum". Finally, the absence of classic Ediacaran macrobiota from these rocks despite evidently favorable conditions for soft tissue preservation upholds the consensus that those organisms were exclusively marine.

As participants in primary production, biological and oxidative weathering, nutrient cycling, river channel stabilization, clay mineralization and pedogenesis, late Precambrian terrestrial (tidal, fluvial, lacustrine and soil) ecosystems may have been important agents of global biogeochemical change (e.g., Kennedy et al., 2006; Kump, 2014; Lalonde and Konhauser, 2015; Lenton and Daines, 2017). However, their fossil and geochemical records are sparse and somewhat controversial (e.g., Wellman and Strother, 2015). While claims have been made for a terrestrial Ediacaran macrobiota (e.g. Retallack, 2016), this conflicts with sedimentary evidence indicating that all known Ediacaran macroorganisms resided within marine environments (Grazhdankin, 2003; Wood et al., 2003, Ichaso et al., 2007, Tarhan et al., 2017, Maloney et al., 2020; McMahon et al., 2020). Putative microbially induced sedimentary structures (MISS) are, however, commonly reported in late Ediacaran tidal and fluvio-tidal siliciclastic sediments worldwide (Davies et al., 2016; their Table 1).

Here we report fossil terrestrial life from the late Neoproterozoic siliciclastic rocks of the Signal Hill Group, Avalon Peninsula, Newfoundland, Canada. The Avalon Peninsula preserves a >7.5

km-thick late Neoproterozoic volcano-sedimentary succession deposited close to the shoreline of

the micro-continent Avalonia (Murphy and Nance, 1989; **Supplementary Figure 1**). The

succession shows an overall shallowing-upwards trend from deep-marine basin-floor facies to

shallow-marine and ultimately emergent siliciclastic units (Williams and King, 1979; Gardiner

and Hiscott, 1988; Wood et al., 2003). The uppermost Signal Hill Group records the transition to

non-marine conditions. Coastal exposures in the area around Ferryland span a stratigraphic

thickness of c. 1.5 km (Supplementary Figure 1). In this area, the basal Cappahayden Formation

and overlying Gibbett Hill Formation represent deposition within shallow marine, wave-

influenced, and increasingly sand-dominated environments (Matthews, 2011). The up-section

gradational transition from the thickly-bedded grey cross-stratified and rippled sandstones of the

Gibbett Hill Formation into the Ferryland Head Formation, defined by the appearance of red

sandstones (Williams and King, 1979), records the onset of periodically emergent deposition

(Matthews, 2011). The 'E' Surface at Mistaken Point (**Supplementary Figure 1**), famous for its

rangeomorph fossils (a clade of soft-bodied organisms comprising one or more fractal-like

'fronds') has recently been dated to 565.00 ± 0.64 Ma (Matthews et al., 2020). While the units

cropping out in Ferryland are >1.5 km stratigraphically above the 'E' Surface, they are also 50

km to the north and were deposited in a southwards-prograding system (King, 1990) — note that

this diachroneity could imply an age closer to c.565 Ma than might otherwise be expected. In any

case, the Signal Hill Group pre-dates the Ediacaran–Cambrian transition (e.g. Gehling &

Narbonne, 2000; Myrow, 1995; Wood et al., 2003; Billings, 1872). While the upper boundary of

the Group does not crop out in the area, a correlative section in the Musgravetown Group is

unconformably overlain by the Lower Cambrian Random Formation (King, 1990). Here we

report the presence of exquisite mouldically preserved desiccated microbial mat fossils in the

Gibbett Hill Formation, abundant Arumberia-type fossils in the Ferryland Head Formation, and associated metre-scale structures we interpret as fossil streamers produced by current-induced biofilms.

Results and Interpretation

Desiccated microbial mats with "flip-overs"

The Gibbett Hill Formation has previously been described as a succession of thickly bedded grey and buff sandstones deposited in shallow marine environments (Williams and King, 1979; Matthews, 2011). At Bear Cove Point (46°56'26"N 52°53'31"W), within ~40 m of the base of the Formation at a site and stratigraphic position where fossils have not previously been discovered, we observe siltstones and mudstones interbedded among the more abundant sandstones. These rocks host sharp-crested, symmetrical ripple marks, which we interpret to record wave activity, as well as multiple horizons with sedimentary cracks suggestive of desiccation **(Supplementary Figure 2)**. At this locality, we report fossil microbial matgrounds, exceptionally well preserved in epirelief on sandstone bedding planes capped by mudstone veneers. One such surface displays a semi-polygonal network of shallow fossil shrinkage cracks, which are bordered by slightly raised, flat-topped strips and wedges (**Supplementary Figure 3**; **Figure 1A**). Most of the cracks are dm-scale in length and open to a width of several cm; they are preserved with sub-millimetric epirelief. The cracks are bordered by slightly raised, flat-topped strips and wedges that have sharply defined but irregular edges and are consistently just under half the diameter of the cracks they border. Based on comparisons with modern tidal microbial mats (**Supplementary Note 1**) and with fossil MISS (e.g., Noffke, 2009), we interpret these raised features as the results of the

desiccation-shrinkage of smooth, ductile, coherent, epibenthic microbial mats exposed to air.

Shrinkage caused the crack margins to peel back, widening the cracks to several cm and forming

inverted flaps ("flip-overs" *sensu* Eriksson et al., 2007) that are retained in sub-mm detail on the

bedding plane (**Figure 1B**). Thus, the relief of the bedding plane preserves a mould of the top of

the mat including these flaps, rather than simply the impression made by the mat on the

underlying sediment, as in some MISS. To our knowledge, such well preserved examples of

microbial mat flip-overs have not previously been found in the siliciclastic fossil record of any

period, although less well preserved examples are reported (e.g., from the Palaeoproterozoic

[Eriksson et al., 2000, 2007], Mesoproterozoic [Beraldi-Campesi et al., 2014] and Cambrian

[Hagadorn and McDowell, 2012]). A variety of related structures such as "jelly rolls", "roll-ups",

and desiccated mats without clear flip-overs have also been described from the Precambrian

fossil record (e.g., Simonson and Carney, 1999; Eriksson et al., 2000; Noffke et al., 2006, 2008).

At Bear Cove Point, the open cracks also reveal a delicately reticulate surface texture that we

identify as the "elephant skin texture" MISS, well known from under-mat (palaeo)surfaces

(Eriksson et al., 2007; Bottjer and Hagadorn, 2007; Gehling and Droser, 2009).

Noting previous shallow marine interpretations of the Gibbett Hill Formation, the presence of

wave ripple marks and desiccation cracks on multiple horizons, and the new evidence for

emergence provided by these dessicated microbial mats, it seems likely that the latter inhabited a

tidal setting. The Signal Hill Group as a whole has previously been described as a "shallow

marine to proximal alluvial fan" succession (Myrow, 1995). Our results refine this model,

revealing at least one cycle of deepening and then shallowing after the deposition of the

emergent features described here.

Arumberia and associated structures in the Ferryland Head Formation

Fossil surfaces were studied at Ferryland Head on the eastern coastline of the Avalon Peninsula, Newfoundland, Canada. A c. 10 m thick succession was studied on the northern side of a cove (47°01'13"N 52°51'26"W), situated directly to the north of the lighthouse at Ferryland Head, and south of Bread and Cheese Cove (see **Supplementary Figure 4** for a photographic overview and **Supplementary Figure 5** for a log). This unnamed cove provides both bedding plane and bed-section outcrops of the Ferryland Head Formation, with strata being easily traced along strike for distances of greater than 100 m. At this locality, the stratigraphy can be broadly divided into: (1) a buff-coloured sandstone facies comprising thickly-bedded arkosic sandstones, with occasional tabular cross- and convolute-lamination. Beds are laterally continuous, very gradually pinching out to leave sandstone bodies that can be >100m wide; and (2) a red-brown, comparatively siltstone-rich facies comprising thinly interbedded red-brown mudstones, siltstones, and buff sandstones, in some places showing normal-grading. Sandstone laminae in this facies are generally no thicker than 3 cm, with finer-grained red-brown coloured laminae measuring 1-3 mm thick. Convolute-lamination is not uncommon, with desiccation cracks, and current and wave ripples also being found The studied c.10 m thick succession is dominated by this red-brown siltstone-rich facies.

Previous summaries of the sedimentological evidence (Williams and King, 1979; Sala Toledo, 2004) suggest that the Ferryland Head Formation was deposited in non-marine conditions. We consider the laterally extensive bed geometries and observed sedimentary structures to be indicative of deposition within a braided channel system. The buff sandstone facies is here

considered to be associated with channel and proximal overbank environments, and is observed

to transition upwards into the finer-grained facies. These red-brown interlaminated units are

interpreted to represent braidplain environments of unconfined deposition,influenced by periodic

wetting and drying cycles (producing sedimentary pseudomorphs after gypsum, and desiccation

cracks; **Figure 2A,B**). Wave ripples are found within this facies, potentially representing

deposition in ephemeral braidplain lakes subject to agitation by wind (Lebeau and Ielpi, 2017).

Current ripples are likely to be associated with decelerating unconfined flows (Hampton and

Horton, 2007). Further work is required to assess the extent of tidal influence on these braidplain

environments, and therefore the salinity of the palaeohabitat represented by the fossils reported

here.

The studied c.10 m thick succession is dominated by the red-brown siltstone-rich facies, which

on reddish mudstone horizons preserves diverse microbial mat textures, in some instances cross-

cut by sand-filled desiccation cracks (e.g., **Figure 2B**). Many of these textures can be identified

with known varieties of Arumberia, a problematic sedimentary fabric associated with Ediacaran

matgrounds and characterised by a distinctive, lineated surface texture (see **Supplementary**

Note 2 for discussion of Arumberia nomenclature). Arumberia is well known from late

Ediacaran and early Cambrian intertidal, deltaic, and alluvial plain siliciclastic facies worldwide,

including desiccated sediments (e.g., Glaessner and Walter, 1975; Bland, 1984; McIlroy and

Walter, 1997; Kumar and Pandey, 2008; Kolesnikov et al., 2012; 2021). The classic form

designated 'Arumberia banski' consists of sets of curving, subparallel, equidistant, bifurcating

ridges ('rugae') several cm in length, which fan out over bed surfaces. At Ferryland Head,

arumberiamorph textures vary in scale (e.g., **Figure 2C, D)** and range from 'Arumberia banski'

with well defined parallel 'rugae' (albeit with minimal "fanning out"; e.g., **Figure 2B**) to more

irregular, branching ridges (e.g., **Figure 2E**; cf. 'Arumberia vindhyanensis' Kumar and Pandey,

2008). These features are generally oriented parallel to the palaeocurrent direction inferred from

current ripples in the sandstone immediately underlying them (e.g., **Figure 2E**). The same

phenomenon has been noted in respect of Arumberia 'rugae' at other localities globally

(Glaessner and Walter, 1975; Bland, 1984; Kolesnikov et al., 2012, 2017; McMahon et al.,

2021).

Argillaceous ribbons interpreted as fossil biofilm streamers

A number of bedding planes at Ferryland Head display multiple, elongate, subparallel, gently

curving argillaceous epirelief structures ("ribbons") ~1–20 mm in diameter. Some examples are

directly associated with (and parallel to) Arumberia 'rugae' preserved in the same fashion. The

ribbons that are largest and least similar to previously reported morphologies of Arumberia are

found on an individual bedding plane exposure of ~4 m^2, characterized by a smooth, uneven

surface, probably shaped by currents. This bedding plane, "S1", is found within a section of the

siltstone-rich facies on the northern side of the cove (**Supplementary Figure 4**). The numerous

well-defined ribbons are composed of red-brown clay and silt, contrasting visually with the

underlying buff-coloured fine sandstone; some individual ribbons can be traced for more than a

metre before tapering out, becoming indistinct, or terminating in erosional effacement (**Figure
3A, B**). Except where weathered flat, many of the ribbons protrude slightly from the bedding

plane in positive epirelief.

In plan view, ribbons show a range of enigmatic morphological features (**Figure 3C–H**). They

commonly fork into two or more thinner branches, which typically diverge at low angles (e.g.,

Figure 3C, D). Rarer high-angle branching is also observed (**Figure 3E**). Some ribbons are

connected in complex anastomosing webs (e.g., **Figure 3B,F**) and several appear to cross over

each other (within the same lamina; e.g., **Figure 3G)**. One ribbon contains a discrete, very pale

pink, longitudinally striated portion ~30 mm long, which protrudes convexly upwards from the

bedding plane and evidently differs in material composition from the remainder of the ribbon,

which is argillaceous (**Figure 3H**). To diagnose the composition without damaging this

significant fossil surface, we sampled and thin-sectioned loose material of identical colour and

lustre found within one m stratigraphically. Energy-dispersive X-ray (EDX) spectroscopy

showed that the light pink material was dominated by a phosphate mineral, probably fluorapatite

(**Supplementary Figure 6**).

We consider these megascopic ribbons to be probable fossils. Known abiotic processes are

unlikely to have produced the observed structures, for the following reasons. The features are

roughly perpendicular to a poorly defined set of ripples, which rules out the shrinkage crack

feature 'Manchuriophycus,' which has a sinuous shape running along ripple troughs.

Microchannels and flute marks, while expected to be parallel to flow, are negative rather than

positive epirelief features. Glacial striae are known from the region, but would be more

consistently straight, parallel, groove-like features, not positive, ribbon-like features that branch

and curve. Thin section evidence also rules out the above abiotic interpretations, and shows that

these features are not the bedding expression of tectonic cleavage or fracture networks (**Figure**

4A,B). Thin section and bed section views show that the ribbons are localised to particular

horizons, and lack the laminae-intersecting infill sediments seen in sedimentary structures such

as syneraesis cracks, desiccation cracks, and dewatering structures. It might be suggested that the

ribbons on S1 are the product of selective modern weathering but thin sections demonstrate that the structures continue beneath the exposed surface (e.g., **Figure 4B**); moreover, similar structures are not observed on the multitude of comparably aligned surfaces. Weathering may have enhanced the visual contrast between the better indurated, clay-rich material composing the ribbons and the surrounding lithology. The three-dimensional preservation of the ribbons in argillaceous material (e.g., **Figure 4A,B**), their large size, and their wide spacing rule out interpretation of the structures as being caused by parting lineation, which is only found in sandstones.

Micropalaeontological observations and taphonomic considerations (**Supplementary Note 3**) also support our interpretation of the ribbons as biogenic. The phosphatic replacement seen in one section of a streamer, and the occurrence of stratigraphically proximal phosphatic concretions, imply the liberation of phosphate ions from decaying organic matter (e.g., Battison and Brasier, 2012). In addition, although the S1 surface could not be sampled, similar material sampled five cm higher in the stratigraphy was thin-sectioned at a low angle to bedding, revealing that clay- and phosphate-rich laminae contained filamentous structures that we cautiously interpret as probable fossil microorganisms (**Figure 4C**). These filaments, like the ribbons themselves, appear to have been preserved three-dimensionally by authigenic clay replacement (aluminosilicification), in common with Arumberia at Ferryland Head and at other localities globally (e.g., Kolesnikov et al., 2012). Inded, early replacement of soft tissues by clay minerals has been implicated in the preservation of several important Proterozoic and Phanerozoic Lagerstätten (e.g., Cai et al., 2012; Gabbott et al., 2017). Our observations do not necessarily constrain the timing of clay replacement at Ferryland Head (see **Supplementary**

Note 3 for discussion). Nevertheless, the argillaceous composition of the ribbons and arumberiamorph structures is clearly consistent with an organic origin.

The irregular, anastomosing, web-like morphology of the ribbons (e.g., **Figure 3B**) indicates that they are not large ribbon-shaped individual macroalgae (e.g., vendotaeniaceans). Rather, we interpret them as compressed, aluminosilicified, partly phosphatized, microbial/algal "streamers". Streamers are string-, ribbon-, and rope-like biofilm structures composed of microbes (and/or macroscopic algae) and their extracellular organic substances, ranging from tens of microns to several metres in length. They are commonly found today in very shallow, gently flowing waters, especially those influenced by eutrophication, acid mine drainage, or thermal springs (e.g., Wakao et al., 1985; Dodds, 2006; Ward et al., 2012). Constituent organisms commonly include cyanobacteria, sulfur oxidizing bacteria, thermophilic bacteria (e.g., phylum Aquificales), and green algae (Ward et al., 2012; Takacs-Vesbach et al., 2013; Battin et al., 2016; Vadeboncouer and Power, 2017). Streamers are tethered to the sediment–water (or rock–water) interface at one end, commonly in a benthic microbial mat, and extend downstream, bifurcating and splaying out in the same direction as the current. Thus, streamers differ from mat wrinkles or ridges in being partly detached structures suspended in the water column or resting lightly on the sediment surface. Large streamers tend to be widely spaced but can converge into complex anastomosing networks (**Figure 5A, B**), while smaller streamers commonly form turf-like outgrowths of filamentous mats (**Figure 5C, D**).

The streamer–arumberiamorph spectrum

The co-occurrence at Ferryland Head of megascopic fossil streamers and arumberiamorph mat

textures, both preserved mostly by clay replacements, informs our interpretation of both

phenomena. Reconstructions of Arumberia as a discrete macroorganism (e.g., Retallack & Broz,

2020) are implausible given its indistinct margins and the gradational transitions observed

between different morphologies over short distances (McMahon et al., 2021). Rather, we agree

with previous authors that Arumberia represents an organic matground morphotype arising from

the interaction of dense biotic communities, siliciclastic sediment, and flowing water (Bland,

1984; Kumar and Pandey, 2008; Davies et al., 2016; Kolesnikov et al., 2017; McMahon et al.,

2021). Partial modern analogues may include regularly spaced wrinkles and ridges observed on

cyanobacterial mats in ponds (Kolesnikov et al., 2017), current-parallel microbial wrinkles on

rippled tidal flats (Banerjee et al., 2014), and sub-mm, current-parallel ridges produced in

laboratory experiments using fluvial biofilms (Neu and Lawrence, 1997). However, we propose

that the raised ribbons and lineations on fossil arumberiamorph surfaces include not only ridges

(or 'rugae') but also the remains of streamers (which may be identical with the "cords" described

by McMahon et al., 2021, who report positive and negative epirelief examples from NW France).

These streamers may usually have been smaller and more mat-like than the megascopic ribbons

dominating horizon S1 at Ferryland Head (e.g., compare **Figure 2C** and **Figure 5D**). It can be

difficult to discriminate between streamers and linear mat thickenings from preserved epirelief

alone, but thin sections orthogonal to the lineation direction can provide decisive evidence.

Ridges ('rugae') manifest as laminated clay-rich, tent-like convexities (e.g., Kolesnikov et al.,

2017; their Figure 4C). By contrast, streamers form discrete, rather flat, argillaceous ribbons

(**Figure 4A**; sample is from horizon S2, also shown in **Figure 2E**). Ribbons can also exhibit a

compressed bull's-eye pattern with a clay-rich core and a mantle of silt, draped by overlying clay

laminae (**Figure 4B**, from the same surface). This internal grain-size patterning appears to be

topologically incompatible with a 'rugose' thickening or wrinkle in a microbial mat, but is explained by our interpretation of these features as streamers that lived in partial suspension and were buried with a passively acquired coating of silt. Biomass, both streamer and microbial mat, was then apparently replaced by clay.

The associations observed at Ferryland Head suggest that Arumberia matground structures and streamers of all sizes do not represent different organisms but, rather, a spectrum of patterns of spatial organization manifested by substantially similar communities. The affinities of these organisms are not obvious; comparison with modern arumberiamorph mats (Kolesnikov et al., 2017) and large modern streamers suggests that they were autotrophic (chemotrophic or phototrophic) and could have been largely (cyano)bacterial, but we cannot exclude the possibility that eukaryotes were also present. The filamentous microfossils associated with the streamers (**Figure 5C**) are consistent in size and morphology with both cyanobacteria and eukaryotic microalgae. The mode of preservation by clay minerals may result from bacterially mediated reactions but is consistent with either bacterial or eukaryotic affinity for the fossils themselves (Konhauser & Urrutia, 1999; Newman et al., 2016; Anderson et al., 2020). The discovery of ribbon-like microbial communities preserved in a terrestrial lithology has at least one precedent in the form of mm–cm-scale, carbonaceous "strap-shaped" cyanobacterial fossils from the early Silurian of Virginia (Tomescu et al., 2006), suggested here to be possible fluvial streamers.

The diversity of macroscopic arumberiamorph textures and streamers at Ferryland Head was most likely shaped by variations in hydrodynamic conditions such as shear stress and turbulence.

These responses may have fallen on a continuum, with weak currents supporting the development of 'rugose' arumberiamorph textures, while stronger currents drew out suspended streamers (**Figure 6**) given enough time. This "streamer–arumberiamorph spectrum" model sheds new light on occurrences of Arumberia elsewhere in the world. For example, many specimens of 'Arumberia banksi' show fan-shaped patterns and small, scattered domes; both features that can be observed in modern streamer mats (e.g., **Figure 5D**). The mm–cm-wide longitudinally striated ribbons of 'Arumberia ollii', and the parallel or fanning, 0.5 mm-diameter curved filaments of 'Arumberia beckeri', both reported as aluminosilicified compressions from the Ediacaran of the Central and South Urals by Kolesnikov et al., 2012, can now also be interpreted as small streamers similar to those at Ferryland Head. Kolesnikov et al. (2012) suggested that these two forms might be taphonomic variants of each other, and Kolesnikov et al. (2017) proposed that they were both unrelated to 'Arumberia' since they consist of discrete elements rather than textures on a mat. Our model suggests that they probably belong on a spectrum with arumberiamorphs, and predicts that intermediates may exist. We also note that streamer-mats preserved on bedding planes have previously been reported from Devonian hot spring sinter deposits; these define a surface texture aligned to and preserved within palaeo-channels that may be similar to the textures observed at Ferryland Head, and show a finely laminated structure in cross-section (Walter et al., 1996). Our results, and our reinterpretation of Arumberia, extend the fossil record of terrestrial streamer formation into the Precambrian.

Discussion

The exceptionally preserved flipped-over desiccated microbial mats preserved at Bear Cove Point, as well as the ribbon-like current-induced streamers at Ferryland Head, provide new windows onto late Ediacaran life on land. Photosynthetic algal and microbial biofilms and streamers commonly dominate primary production in streams and rivers today; their biomass is held in check largely by grazing animals (Vadeboncoeur and Power, 2017). Streamers can also be found in tidal settings (e.g., Lakhdar et al., 2021, their Fig 9C) but are often most abundant where animal activity is suppressed, as in hot springs and acidic streams (Doemel and Brock, 1977; Lear et al., 2009).

Although a profusion of microbial and algal life can be associated with high nutrient fluxes, the abundance of arumberiamorph mats and streamers at Ferryland Head — and of arumberiamorphs in analogous late Ediacaran settings globally — may be more likely to reflect the lack of animal activity on land during this period. Indeed, the absence of "classic" Ediacaran macrofossils (including metazoans; Dunn et al., 2019) in the terrestrial deposits of the St. John's Group is well attested (e.g. Williams and King, 1979; Matthews, 2011). The discovery of well preserved macroscopic fossils (albeit of probable communal microbial origin) in at least two taphonomic modes (aluminosilicification and phosphatization) within this fluvioterrestrial succession suggests that this absence is not simply preservational, and supports the general consensus that complex macroorganisms, although well established in marine systems, had not yet colonised terrestrial settings.

The discovery of large streamers suggests that microbial and perhaps algal life was highly abundant in some terrestrial settings by the late Ediacaran. Indeed, the abundance of

arumberiamorph mats alongside the streamers at Ferryland Head, and their ubiquity in similar rocks globally, suggest that late Ediacaran fluvio-tidal systems could accumulate substantial photosynthetic and/or chemotrophic biomass; the apparent absence of animals was not for want of a food source. We note that microbial communities can potentially increase sediment cohesion on channel-bounding flood plains (van der Vijsel et al., 2019) and thus also affect the preserved architecture of fluvio-tidal systems (Ielpi et al., 2018; Brückner et al., 2021). Future studies of late Ediacaran nutrient cycling, non-marine sedimentology, and the rise of life on land should take these results into account.

Methods

Optical microscopy was undertaken with a Leica DMLP reflected/transmitted light polarizing microscope with DFC 420C camera and Leica Application Suite v 4.00. For compositional analysis of carbon-coated, polished, uncovered thin sections, scanning electron microscopy was undertaken at the Analysis and Characterization facility of the Aberdeen Centre for Electron Microscopy, University of Aberdeen, using a Carl Zeiss GeminiSEM 300 VP equipped with an Oxford Instruments NanoAnalysis Xmax80 X-ray energy-dispersive spectrometer.

Sample availability

Thin sections figured in this paper (FRY-10 and NL-3), and corresponding hand samples, have been deposited at the Cockburn Museum, University of Edinburgh, under accession number EUCM.0001.2021. No permits were required to sample at the localities studied in this work.

Acknowledgments

Figure captions

Figure 1: Exquisite mouldic preservation of a microbial mat with desiccation features. A: Photograph of a mudstone veneer capping a sandstone block in the Gibbett Hill Formation at Bear Cove Point, Newfoundland. Scalebar is in cm. **B:** Reconstruction of the microbial mat showing sharply defined overfolded crack margins and exposed undermat layer.

Figure 2: Sedimentary structures on bedding planes in the Ferryland Head Formation, siltstone facies. A: Angular pseudomorphs after gypsum in a mudstone lamina. **B:** Arumberia, a putative microbial matground fossil comprising subparallel curving ridges ('rugae'), which are here oriented lower-left to upper-right. Black arrows indicate a sand-filled desiccation crack in the otherwise argillaceous lamina. The white arrow indicates the edge of a second, overlying Arumberia layer. **C:** Arumberiamorph texture with linear ridges ~0.5 mm in diameter, some of which overlap each other. **D:** A more coarsely lineated, somewhat ribbon-like arumberiamorph texture. **E:** A sandstone surface showing gentle undulations best interpreted as ripple marks (Horizon S2, **Supplementary Figure 3**). A highly branching form of Arumberia is preserved as an argillaceous red veneer, with lineations consistently aligned perpendicular to the ripple crests, i.e., in the same direction as the inferred palaeocurrent. **Inset:** Close-up view of area indicated, showing complex nature of the lineated, arumberiamorph surface texture.

Figure 3: Argillaceous ribbon-like structures on a sandstone bedding plane at Ferryland Head (Horizon S1, Supplementary Figure 3). A: Field photograph and interpretative sketch (based on multiple photographs) of a fine sandstone bedding plane assemblage of reddish argillaceous ribbon-like structures showing the positions illustrated by figure panels B–H. **B:** Photograph of the same surface with a narrower field of view, showing multiple branching and converging ribbons. **C:** Photograph and interpretative sketch of a low-angle bifurcation (arrowed). **D:** Photograph and interpretative sketch of a low-angle multifurcation. **E:** Photograph

and interpretative sketch of a curved, high-angle bifurcation. **F:** Photograph and interpretative sketch of interconnected ribbons. **G:** Photograph and interpretative sketch showing one ribbon crossing over another at arrowed position. **H.** Ribbon with light coloured, 30 mm-long, convex portion; close-up shows longitudinal lineations visible when wetted. Photographs have been enhanced for contrast.

Figure 4: Photomicrographs of small argillaceous ribbons (A,B) and poorly defined filaments (C,D) in thin sections from Ferryland Head. A: Transverse section through small raised argillaceous ribbon (arrowed) interpreted as a fossil microbial streamer from horizon S2, occurring on bedding plane (Supplementary Figure 3; Figure 2E). Thin Section FRY-10. **B:** Transverse section through a second streamer (arrowed) on the same bedding plane as A (thin section FRY-10), mantled with silt and sandwiched between argillaceous laminations to form a concentric bull's-eye pattern. Argillaceous laminae above and below the streamer were deflected by silt and/or authigenic cements during compression. **C:** Two views of thin section NL-3 cut at low angle to bedding, showing poorly defined filaments that we interpret as probable microfossils. Note preferred orientation of filaments in the upper image. Sample collected c. 5 cm above S1 streamer-bearing horizon.

Figure 5: Modern examples of shallow-water algal and microbial streamers. A: Long, ropy green streamers in a shallow stream (1–2 metres across) near Lufkin, Texas, USA. Photograph courtesy of Angelina & Neches River Authority Clean Rivers Program. **B:** Sinuous green streamers in a rocky, gently flowing stream near Deiva Marina, Liguria, Italy. Individual streamers diverge, reconverge, and anastomose. **C:** Small streamers in fast-flowing hot springs at

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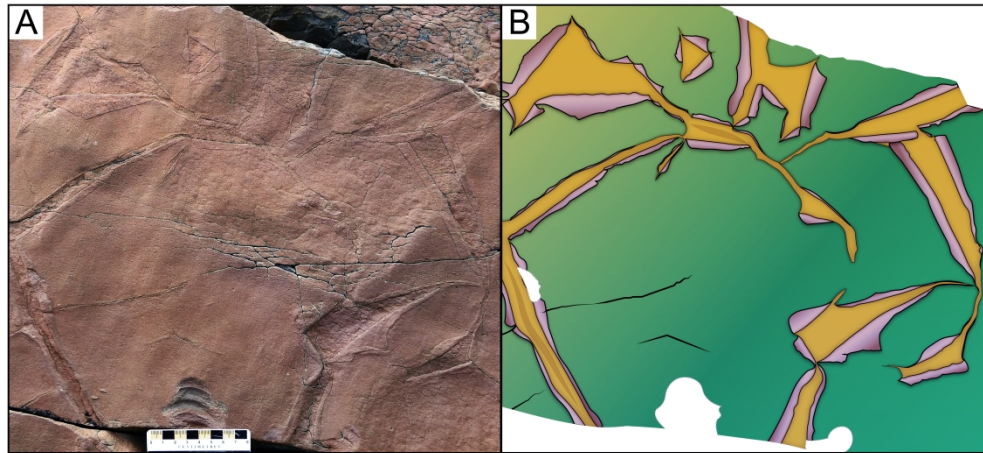
Figure 1: Exquisite mouldic preservation of a microbial mat with desiccation features. A: Photograph of a mudstone veneer capping a sandstone block in the Gibbett Hill Formation at Bear Cove Point, Newfoundland. Scalebar is in cm. B: Reconstruction of the microbial mat showing sharply defined overfolded crack margins and exposed undermat layer.
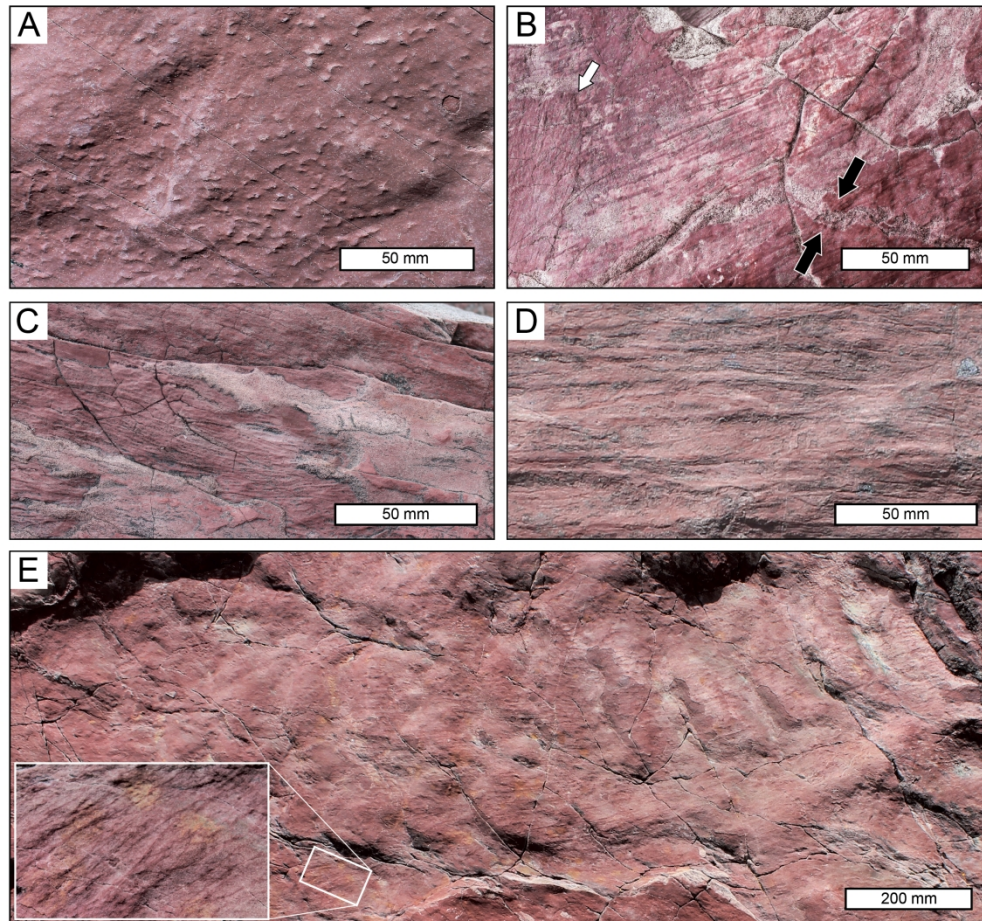
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Figure 2: Sedimentary structures on bedding planes in the Ferryland Head Formation, siltstone facies. A: Angular pseudomorphs after gypsum in a mudstone lamina. B: Arumberia, a putative microbial matground fossil comprising subparallel curving ridges ('rugae'), which are here oriented lower-left to upper-right. Black arrows indicate a sand-filled desiccation crack in the otherwise argillaceous lamina. The white arrow indicates the edge of a second, overlying Arumberia layer. C: Arumberiamorph texture with linear ridges ~0.5 mm in diameter, some of which overlap each other. D: A more coarsely lineated, somewhat ribbon-like arumberiamorph texture. E: A sandstone surface showing gentle undulations best interpreted as ripple marks (Horizon S2, Supp. Figure 3). A highly branching form of Arumberia is preserved as an argillaceous red veneer, with lineations consistently aligned perpendicular to the ripple crests, i.e., in the same direction as the inferred palaeocurrent. Inset: Close-up view of area indicated, showing complex nature of the lineated, arumberiamorph surface texture.
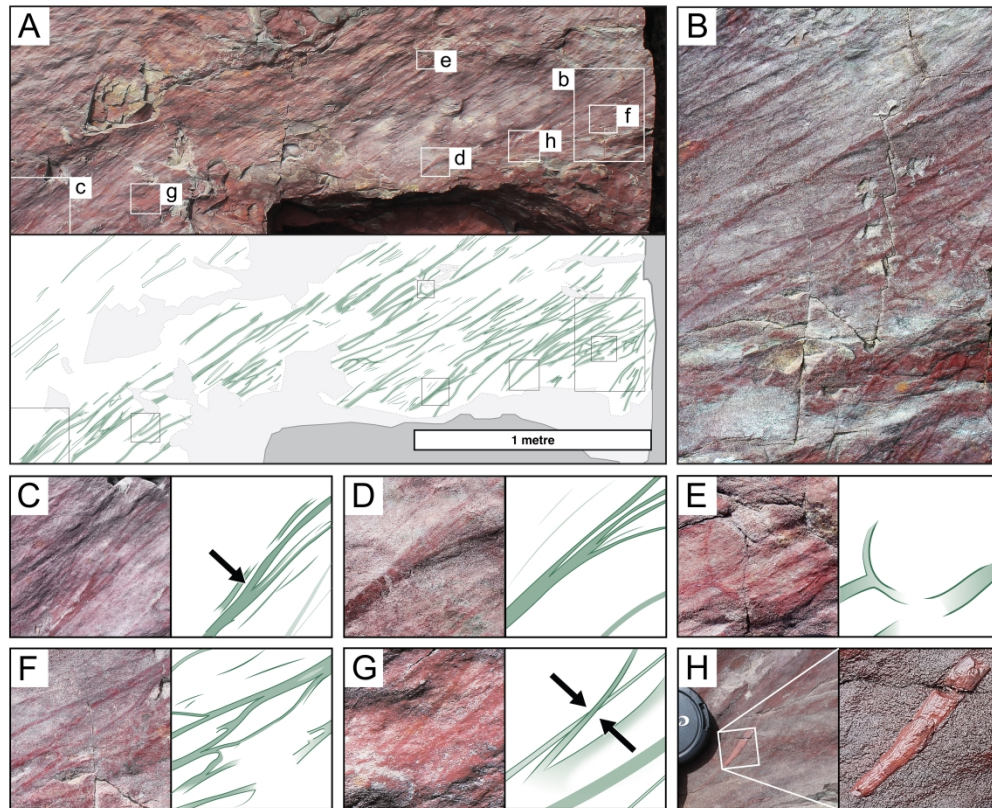
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Figure 3: Argillaceous ribbon-like structures on a sandstone bedding plane at Ferryland Head (Horizon S1, Supp. Figure 3). A: Field photograph and interpretative sketch (based on multiple photographs) of a fine sandstone bedding plane assemblage of reddish argillaceous ribbon-like structures showing the positions illustrated by figure panels B–H. B: Photograph of the same surface with a narrower field of view, showing multiple branching and converging ribbons. C: Photograph and interpretative sketch of a low-angle bifurcation (arrowed). D: Photograph and interpretative sketch of a low-angle multifurcation. E: Photograph and interpretative sketch of a curved, high-angle bifurcation. F: Photograph and interpretative sketch of interconnected ribbons. G: Photograph and interpretative sketch showing one ribbon crossing over another at arrowed position. H. Ribbon with light coloured, 30 mm-long, convex portion; close-up shows longitudinal lineations visible when wetted. Photographs have been enhanced for contrast.
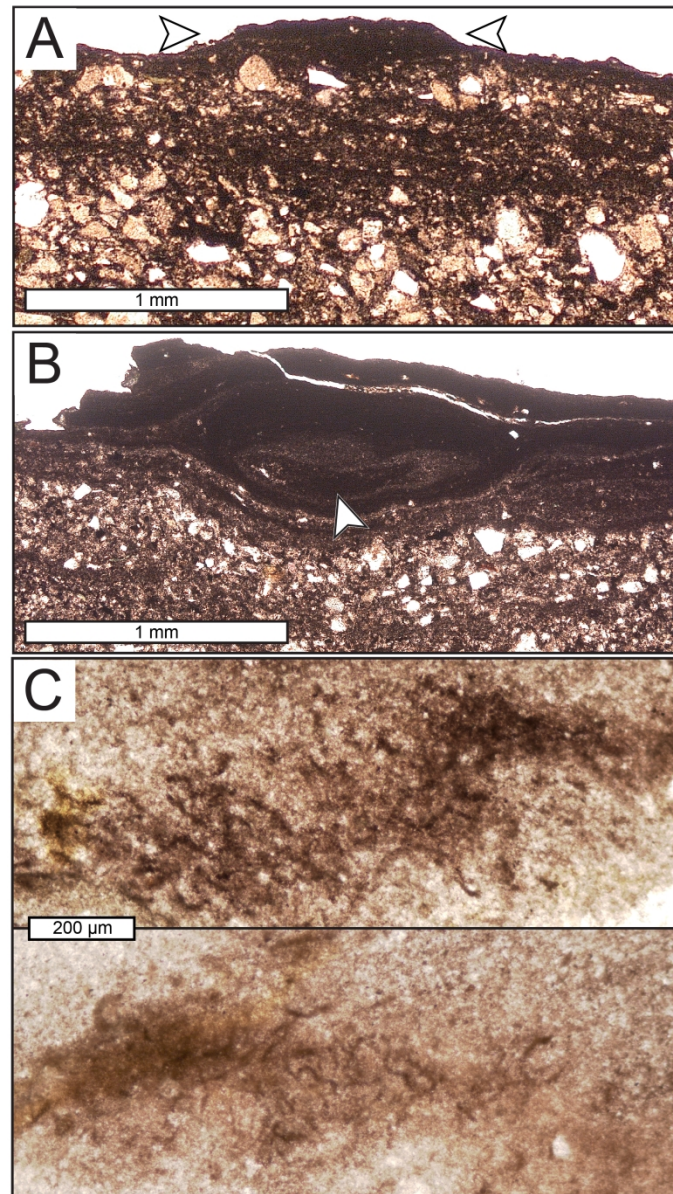
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Figure 4: Photomicrographs of small argillaceous ribbons (A,B) and poorly defined filaments (C,D) in thin sections from Ferryland Head. A: Transverse section through small raised argillaceous ribbon (arrowed) interpreted as a fossil microbial streamer from horizon S2, occurring on bedding plane (Supp. Figure 3; Figure 2E). Thin Section FRY-10. B: Transverse section through a second streamer (arrowed) on the same bedding plane as A (thin section FRY-10), mantled with silt and sandwiched between argillaceous laminations to form a concentric bull's-eye pattern. Argillaceous laminae above and below the streamer were deflected by silt and/or authigenic cements during compression. C: Two views of thin section NL-3 cut at low angle to bedding, showing poorly defined filaments that we interpret as probable microfossils. Note preferred orientation of filaments in the upper image. Sample collected c. 5 cm above S1 streamer-bearing horizon.
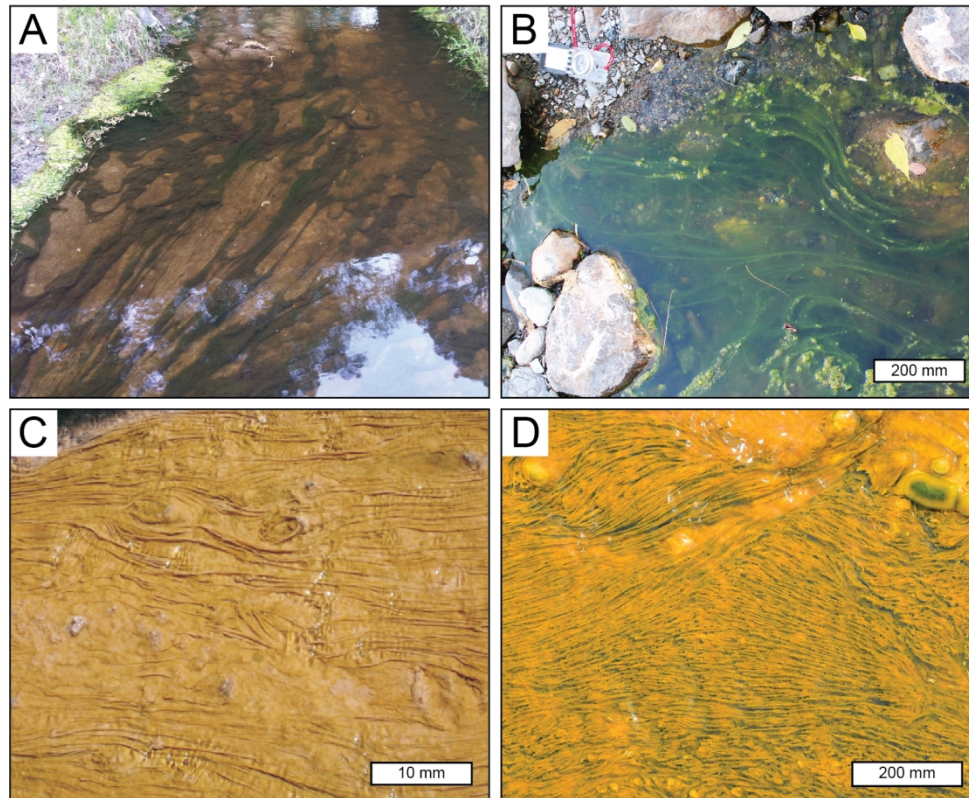
473x832mm (118 x 118 DPI)

Figure 5: Modern examples of shallow-water algal and microbial streamers. A: Long, ropy green streamers in a shallow stream (1–2 metres across) near Lufkin, Texas, USA. Photograph courtesy of Angelina & Neches River Authority Clean Rivers Program. B: Sinuous green streamers in a rocky, gently flowing stream near Deiva Marina, Liguria, Italy. Individual streamers diverge, reconverge, and anastomose. C: Small streamers in fast-flowing hot springs at the El Tatio geyser field, Chile. Photograph courtesy of Gary Smith, Geothermal Scientific Investigations Ltd. D: Streamer-mat in fast-flowing hot springs at Orakei Korako, New Zealand. Photograph courtesy of Gary Smith, Geothermal Scientific Investigations Ltd. The fanning-out behaviour and pustule-like associated structures are comparable to many instances of Arumberia.
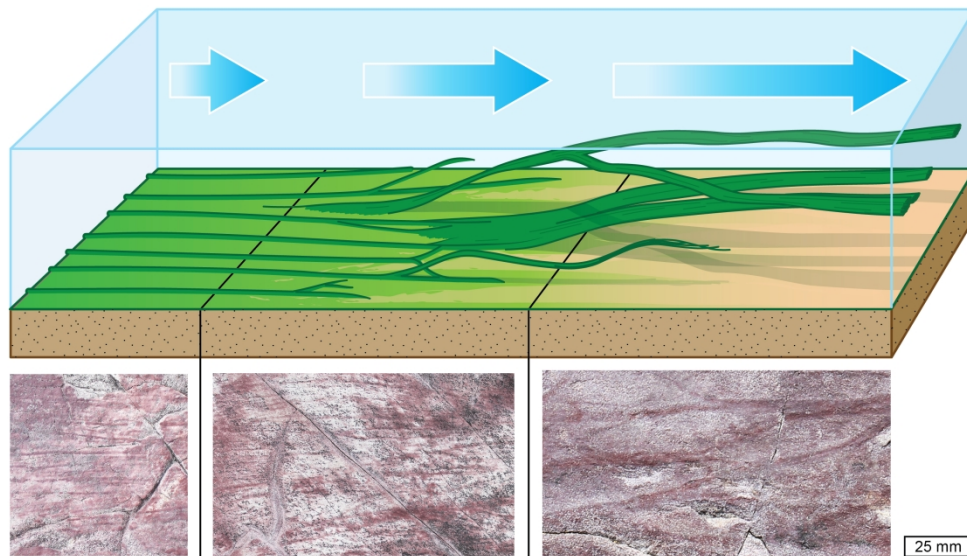
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389x228mm (200 x 200 DPI)