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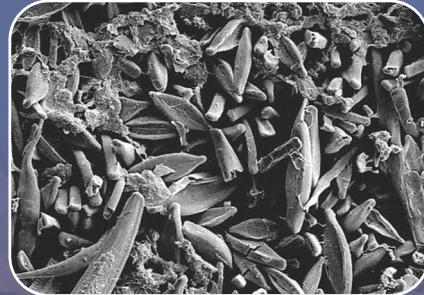
Abstract Book

Lyell Meeting 2017

Sticking Together: microbes and their role in forming sediments

7 March 2017

The Geological Society, Burlington House



Convenors:

Daniel Parsons (University of Hull, UK)

Mike Rogerson (University of Hull, UK)

Concha Arenas Abad (University of Zaragoza, Spain)

Gernot Arp (University of Göttingen, Germany)

Jaco Baas (University of Bangor, UK)



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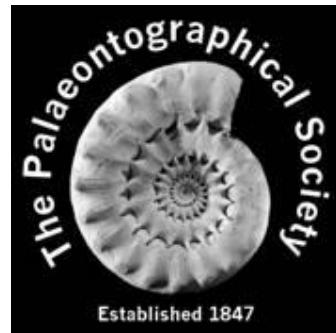
The Lyell meeting is organised by the Geological Society on behalf of the Joint Committee for Palaeontology, which comprises of the Geological Society, the Palaeontological Association, the Micropalaeontological Society and The Palaeontographical Society.



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Society**



Oral Presentation Programme

Tuesday 7 March 2017	
08.30	Registration & tea & coffee (Main foyer and Lower Library)
09.00	Introduction
Open Session: Chaired by Mike Rogerson (University of Hull)	
09.15	Hydrodynamic effects on the structure and functioning of reservoir biofilms: A flume investigation. Dr Sabine Gerbersdorf (Universität Stuttgart, Germany)
09.30	Travertine ridges and microbialite reefs: a rock record of GSL shorelines at Lakeside, Utah. Peter Homewood (Geosolutions TRD & University of Fribourg, Switzerland)
09.45	Insights in the spatial and temporal heterogeneity of microbial and early diagenetic lithification Anneleen Foubert (University of Fribourg, Switzerland)
10.00	The enigmatic cherts at Lake Magadi, Kenya: chemical precipitates, microbialites or both? Robin Renaut (University of Saskatchewan, Canada)
10.15	KEYNOTE SPEAKER: Biofilms and Sediment: a 'Geobiological Tango' Christophe Dupraz (University of Stockholm, Sweden)
10.45	Poster introductions (A-L)
11.00	Tea, coffee and refreshments (Lower Library) Posters (Arthur Holmes)
Session 2: Past into present: Chaired by Concha Arenas (University of Zaragoza, Spain)	
11.30	The 'sediment dilemma' in fossil microbialites: Answers from a Lower Cretaceous microbial paradise Pablo Suarez-Gonzalez (Georg-August-University, Germany)
11.45	Microbes and the phosphatic cementation of heavy-element-rich oil shale in the Green River Formation (Eocene) of Utah, USA Dave Keighley (University of New Brunswick, Canada)
12.00	Microbial mat ecology in lacustrine settings at the Meso-Neoproterozoic boundary Paul Strother (Weston Observatory of Boston College, USA)
12.15	Microbial activity as a key control on fluvial-aeolian landscapes in the Cambrian Arnold Reesink (University of Illinois at Urbana-Champaign, USA)
12.30	Microbial mats as agents in the formation of discoidal pseudofossils: observations from the Ediacaran Longmyndian Supergroup, Shropshire, England Latha Menon (University of Oxford, UK)
12.45	Microbialite mounds of the Mupe Member of the Purbeck Limestone Group (Upper Jurassic), Dorset, southern England Arnaud Gallois (Royal Holloway University of London, UK)
13.00	Lunch (Lower Library) Posters (Arthur Holmes)
Session 3: Chaired by Gernot Arp (University of Göttingen, Germany)	
13.45	Hydrochemistry and biofilm calcification in tufa canal-forming karstic streams ("Steinerne Rinnen", Southern Germany) Gernot Arp (University of Göttingen, Germany)



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14.00	Microbially driven carbonate chimney construction at Mono Lake, California Alexander Brasier (University of Aberdeen, UK)
14.15	Abiotic vs biotic-influenced carbonate nucleation: towards identifying their unique textural signatures Ramon Mercedes-Martín (University of Hull, UK)
14.30	Oxygenic and anoxygenic photosynthesis in a microbial mat from an anoxic and sulfidic spring. Dirk de Beer (Max-Planck-Institute for Marine Microbiology, Germany)
14.45	Modern and ancient biosignatures in sabkha-associated microbial mats Cees van der Land (Newcastle University, UK)
15.00	The combined effects of cyclic particle flux and anaerobic oxidation of methane support growth of a laminated seep bioherm off Pakistan (northern Arabian Sea) Tobias Himmeler (University of Bremen, Germany & IFREMER, France)
15.15	Poster Introductions (M-Z)
15.30	Tea, coffee and refreshments (Lower Library) Posters (Arthur Holmes)
Session 4: Chaired by Jaco Baas (University of Bangor, UK)	
16.00	Not just along for the ride – the influence of extracellular polymeric substances on fine-grained sediment gravity flows Melissa Craig (University of Adelaide, Australia)
16.15	Subaqueous sedimentary cracks: evidence for a microbial contribution Sean McMahon (Yale University, USA)
16.30	Implications of cyanobacterial response to rainfall for dryland stability Joanna Bullard (Loughborough University, UK)
16.45	Microbially-influenced Architectural Preservation in Aeolian Bedforms Robin Westerman
17.00	Microbial transport and soil integrity in drylands David Elliott (University of Derby, UK)
17.15	Biological drivers and sediment behaviour in the Dee estuary, England David Paterson (University of St Andrews, UK)
17.30	Comfort Break
Plenary Session: Chaired by Dan Parsons (University of Hull, UK)	
17.45	Microbial mat sandwiches and other anachronistic sedimentary features of the Ediacara Member (Rawnsley Quartzite, South Australia): Implications for interpretation of the Ediacaran sedimentary record Lidya Tarhan (Yale University, USA)
17.55	Hydraulic, gas exchange and biotic impacts on carbonation of high-pH waters Mike Rogerson (University of Hull, UK)
18.05	How far can biostabilisation go via EPS-mediated sediment erosion process? Xindi Chen (Hohai University, China)
18.15	Visualising the Role of Microbes in the Development of Sediment Flocs Jonathan Wheatland (Queen Mary University of London, UK)
18.15 -19.30	Drinks reception (Lower Library) Posters (Arthur Holmes)
19.30 – 21.00	Optional hot fork buffet (additional charge)



Posters

1. Microbial communities inhabiting hypersaline microbial mats from the Abu Dhabi sabkha

Luiza L. Andrade, Kirsten E. Dutton, Andreas Paul, Cees van der Land, Angela Sherry, Stephen W. Lokier, Ian M. Head
(Lower Library)

2. Textural variations in fluvial stromatolites: a record of biotic and abiotic processes

Arenas-Abad, C., Auqué, L., Jones, B., Martín Bello, L., Osácar, C., Pardo, G. Sancho, C
(Lower Library).

3. What the physical rock record can and cannot reveal about a microbial role in the formation of ancient sedimentary signatures

Neil S. Davies, William J. McMahon
(Lower Library).

4. Carbonate mineralisation in sabkha microbial mats; a comparative study of field and laboratory systems

Kirsten E. Dutton, Andreas Paul, Luiza Lessa Andrade, Angela Sherry, Stephen Lokier, Ian M. Head, Cees van der Land
(Lower Library).

5. Microbialite-coated rafts (giant "oncoids") from the Late Triassic lacustrine succession in the Jameson Land Basin, East Greenland

Li Guo, Steven Andrews, Aurélien Virgone
(Lower Library).

6. Travertine ridges and microbialite reefs: a rock record of GSL shorelines at Lakeside, Utah

Peter Homewood, Michael Vanden Berg, Anneleen Foubert, Jean-Charles Schaegis, Monique Mettraux
(Lower Library). – Poster to accompany oral presentation.

7. Microbialites after mass extinctions: change of life or anachronism?

Stephen Kershaw, Hao Tang
(Lower Library).

8. Biogenicity of fibrous microcrystalline calcite in vadose terrestrial settings

Andrea Martín-Pérez, Adrijan Košir
(Lower Library).

9. Negligible microbial mat influence on ancient river functioning

William J. McMahon, Neil S. Davies
(Lower Library).

10. Microbial processes in Neoproterozoic sediment diagenesis: Evidence in the Aberfeldy stratiform baryte deposits, Grampian Highlands, Scotland

Norman R. Moles, Adrian J. Boyce
(Lower Library).

11. *Gordia* Emmons (1844) – a composite trace fossil from the Hirnantian of the Welsh Basin

Keith H Nicholls
(Lower Library).

12. Microbially Influenced Sedimentary Structures associated with the Hirnantian extinction episode in the Welsh Basin

Keith H Nicholls
(Lower Library).

13. Evolving use of ecospace in early Phanerozoic deep-marine environments revealed by biosedimentary structures and ichnofabrics

Sean Burke, Patrick J. Orr, Peter D.W. Haughton, Stuart L. Kearns
(Arthur Holmes)

14. Lithification of laminated microbial mats in the coastal sabkha of Abu Dhabi (UAE)

Andreas Paul, Luiza Lessa Andrade, Wesley M. Court, Kirsten E. Dutton, Ian M. Head, Cees van der Land, Stephen W. Lokier, Angela Sherry
(Arthur Holmes)

15. Microbial Biofilms drive Global Carbonate Production Rates

Martyn Pedley & Mike Rogerson
(Arthur Holmes)

16. Recognizing microbial mats in fluvial-tidal siliciclastic deposits affected by very low-grade metamorphism: comparison of the dinosaur track-bearing Oncala Gr (Lower Cretaceous, N Spain) with present-day examples from Argentina

I.E. Quijada, D.G. Cuadrado, M.I. Benito, L. Maisano, P. Suarez-Gonzalez, R. Mas, S. Campos-Soto, L. Fernández-Labrador, J. Pan, M. Rodríguez-Martínez
(Arthur Holmes)



17. Microbial activity as a key control on fluvial-aeolian landscapes in the Cambrian

A.J.H. Reesink; J.L. Best; J.T. Freiburg; D.F. Dominic; R.W. Ritzi
(Arthur Holmes) – Poster to accompany oral presentation.

18. Influence of sterile Extracellular Polymeric Substances on calcite growth and trace element incorporation

M. Rogerson, P. Saunders, J.D. Wadhawan, G. Greenway, H.M. Pedley
(Arthur Holmes)

19. The role of bacteria in the generation and biodegradation of petroleum

Fivos Spathopoulos
(Arthur Holmes)

20. 'Giant microbialites': from thrombolites to stromatolites and back again.

Upper Miocene, Mallorca (Spain)
Suarez-Gonzalez, P., Arenas-Abad, C., Pomar, L., Benito, M.I.
(Arthur Holmes)

21. Mineral precipitates in modern microbial mats: crystallites, spheroids, bacteria, vesicles and viruses

Maurice Tucker, Edoardo Perri, Mirek Slowakiewicz, Fiona Whitaker, Leon Bowen
(Arthur Holmes)

22. Pilbara Oddities

Edwin Willey
(Arthur Holmes)

23. Biofilm origin of clay coated sand grains and sediment heterogeneity within estuarine systems

Luke J. Wooldridge, Richard H. Worden, A. Thompson, Joshua Griffiths, James E. Utley, Robert A. Duller, P. Chung
(Arthur Holmes)

24. Carbonates in hyper-alkaline settings: lessons from modern systems and implications for South Atlantic "Microbialites"

V Paul Wright, Louis Emery, Nicholas J Tosca, Lesley Cherns
(Arthur Holmes)

25. Microbial, biotic or not? Spherulitic calcites and the critical role of Mg-silicate hosts

V Paul Wright, Andrew J Barnett, Nicholas J Tosca
(Arthur Holmes)

26. Yellow aragonite cement in methane-seep deposits results from biofilm mineralization

J. Zwicker, D. Smrzka, W. Bach J.L. Goedert, J. Peckmann
(Arthur Holmes)



Oral Presentation Abstracts

Hydrodynamic effects on the structure and functioning of reservoir biofilms: A flume investigation

Dr J. A. Hope¹, Prof. S. Wiprecht¹ and Dr. S. U. Gerbersdorf¹

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The management of reservoir systems can impact geomorphological, hydrological and ecological processes up- and down-stream of the dam. For example, the magnitude and frequency of floods may be mediated by dam management and the hydrological stability of rivers downstream may be enhanced by good management practice. Nevertheless, there remains a lack of information available on how management impacts ecosystem functioning within the reservoir itself, in particular the role of biological stabilisation of reservoir sediment and sediment behaviour.

The effects of hydrodynamic conditions on the structure and function of biofilms has previously been investigated. For example, biofilms developing under higher flow velocities have displayed greater biofilm development in microfluidic channels (Kim et al., 2013) as well as greater resistance to erosion in fluvial sediments when developed at higher flow (Thom et al., 2015a). Reservoir systems are generally subject to fairly moderate hydrodynamic regimes or disturbances, with floods and reservoir flushing events significantly increasing the bed shear stress, however in general the force on the bed may be relatively low for the majority of year. Despite the undoubtedly importance of sediment biofilms (primary production, sediment stability, nutrient and carbon cycling) there is a paucity of information regarding the role of biofilms in reservoirs.

For these reasons, this presentation will document the short term (<30 days) dynamics of mature biofilms exposed to high shear stress, with biofilms cultivated under initially typically low shear stress prior to treatment. The adaptation of the biofilm over prolonged exposure to high bed shear stress was recorded by documenting biochemical properties and sediment adhesion as a proxy for sediment stability. The results will provide valuable reference data for the management of reservoir systems and elucidate the functional role of biofilms, with a particular focus on the resistance to erosion within reservoirs and community dynamics.

NOTES



Travertine ridges and microbialite reefs: a rock record of GSL shorelines at Lakeside, Utah

Peter Homewood^{1,3}, Michael Vanden Berg², Anneleen Foubert³, Jean-Charles Schaegis³, Monique Mettraux^{1,3}

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Spectacular outcrops of fissure ridge and dome travertine, directly linked to microbialite biostromes, are associated with a number of bedrock headlands that jut out along the Great Salt Lake shoreline at Lakeside (Figure 1). Highly fractured Mississippian Great Blue Limestone bedrock allowed alkaline fluids to flow through an open network, feeding the fissure ridge-dome systems.

Laminated aragonite facies are preserved in bedrock fractures, and thrombolitic drapes spread from these to form metre-thick bedrock coats. A pronounced domal structure, about 2m in height and 30mx15m in plan view extends from the travertine-encrusted headland of Lakeside Ridge. Partial erosion of the dome crest reveals a layered composition comprising travertine and tufa facies, which progressively built up the domal shape (Figure 2). Alkaline waters were fed from fissure vents cutting vertically through the dome with a criss-cross pattern. Laminated facies spread out from the fissures to nourish layered thrombolites conformable with the domal structure. Mineralogy of the dome is aragonite and/or non-stoichiometric dolomite. Numerous metre-scale ponds with vertical cascade fronts stepped down the flanks of the domal structure. Pond facies successions indicate fluctuating flow of alkaline fluids from the bedrock aquifer source, while lake level rose and fell covering and exposing the ponds during growth. The drop wall coatings, outward growths of clotted calcite shrubs, have been dated at 12,5kyrs (radio carbon age) by Pedone & Dickson (2000).

Embayments between the headlands record a lakeward succession of facies: high shoreline travertine aprons with small feeder channels and ponds, mounds and encrustations; inner shore zone layered “monk’s head” microbialite mound reefs (Figure 3, 4); intermediate shore zone “molar tooth” columnar microbialite mound reefs (Figure 5, 6); outer shore zone, scattered m-scale low relief microbialite mounds. The microbialite reefs are shore parallel biostromes, and sedimentary structures of associated arenites to conglomerates indicate beach swash zone environments for “monk’s head” mounds. Wave rippled substrates suggest deeper water for the “molar tooth” mounds. Wave front directions deduced from ripple crests and tabular foresets fit well with the fetch directions for Lakeside and Strong’s Knob given by Atwood (2006). Fine sediment between the larger m-scale mounds suggests an offshore environment for these.

The record of littoral to shoreline microbialites and tufa mounds at Lakeside lies in the elevation range of 1282m to 1286m. Between these heights, high frequency lake level fluctuations and a longer-term falling trend are recorded by facies. Microbial mat covered mounds, previously under several metres of water, lie a kilometre away at the current low stand level of 1277m. A wide spectrum of geochemical analyses, age dating and detailed petrography is placing this remarkable lake margin record within the known fluctuations of shorelines since the lake fell from the Bonneville and Provo high stands. Furthermore, the outcrop continuity of groundwater fed travertine and tufa to lake-water buffered microbialites,



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with feeder channels leading down from headlands to microbialite shoreline biostromes, should allow establishing chemical proxies for the mixing of the aquifer fluids with the varying salinity of lake waters. The results may also provide insights on the debate over chemical and microbial origins of lacustrine carbonates.



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1) Drone panorama of Lakeside Ridge headland and fissure ridge travertine and tufa mound. Note 4x4 vehicle and bulldozer near causeway for scale.

2) Fissure ridge dome and feeder vent. Kneeling person gives the scale.

3) “Monk’s Head” microbialite biostrome linked to headland tufa (background) by a feeder channel. Kneeling person gives the scale.

4) Slab of “Monk’s Head” microbialite showing tonsure-like growth of layering. 10cm scale.

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- 5) "Molar Tooth" microbialite reef. Three persons in background provide scale.
6) Slab of "Molar Tooth" microbialite with upward branching or radiating columns. 10cm scale.

ATWOOD, G. 2006. *Utah Geol. Surv. Misc. Publ. 06-9* 1-231. ISBN 1-55791-761-2

PEDONE, V.A. & DICKSON, J.A.D. 2000. *Journal of Sedimentary Research*, **67**, 1152–1159.



NOTES



Insights in the spatial and temporal heterogeneity of microbial and early diagenetic lithification

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Microbial carbonates are unique deposits formed by the direct or indirect action of microbes. They witness early Life since Precambrian times, and inhabit a wide variety of environments - from marine to continental settings. Processes involved in the formation of such microbialites remain to be unveiled. Moreover, early diagenesis is often obliterating the primary facies, fabric and geochemical signals, rendering the interpretation of microbial structures difficult.

This study highlights the importance of multi-scaled X-ray computed tomography and 3D-visualization at micro- and meso-scale combined with field (in-situ) and lab (in-vitro) experiments to understand the precipitation mechanisms and early diagenesis of microbial mediated Ca-Mg carbonates in a wide variety of settings. Different case studies have been selected showing how in-situ 3D visualization may unveil the pathway from crystal nucleation over crystallization till sedimentary fabric formation and early diagenesis.

The first case study focuses on marine and hypersaline microbialites deposited in an active rift setting from the Danakil Depression in Ethiopia, Afar. The second case study presents field precipitation experiments on different substrates of continental tufa deposits in the Gotteron Valley (Fribourg, Switzerland) and of hot spring deposits in Greece and Hungary. The last case study visualizes microbial-mediated precipitates in biofilms produced under aerobic and anaerobic conditions in constrained lab experiments.

Samples have been measured with the Bruker Skyscan 2211 (multi-scale X-ray nano-CT system) using an open X-ray source (energies varying between 60 and 120 kV, <4W) with Be-window. Two types of detectors have been used (resp. the 6 Mp flatpanel detector and the 11Mp cooled CCD detector) and voxel resolution was varying between 500 nm and 10 micrometer. Filter-sets were evaluated to enhance the segmentation of different carbonate minerals (calcite, dolomite, aragonite). Defined carbonate standards have been added during the scans facilitating segmentation. Images have been reconstructed using InstaRecon. Image segmentation and visualization have been performed using resp. CT-An, CT-Vox and Avizo (FEI).



NOTES



The enigmatic cherts at Lake Magadi, Kenya: chemical precipitates, microbialites or both?

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Chert is abundant in the Pleistocene sediments of Lake Magadi, a hypersaline alkaline lake in the southern Kenya Rift. Those cherts ('Magadi-type chert' of Eugster, 1969) were long attributed to early diagenetic alteration of magadiite ($\text{NaSi}_7\text{O}_{13}\text{OH}_3 \cdot 4\text{H}_2\text{O}$) until Behr and Röhricht (2000) showed that some of the cherts preserve microbial fossils. Behr (2002) proposed that many of the cherts might be microbialites and questioned whether *all* cherts at Magadi are Magadi-type chert. He suggested that some cherts might have had soft siliceous precursors or have replaced carbonates.

The exposed cherts were examined as part of a reassessment of the stratigraphy and geological history of the Magadi basin. Behr (2002) recognised several groups of chert based on stratigraphic position and morphology. The two most important groups are *bedded cherts*, of different ages, and *intrusive cherts* where the silica penetrated younger sediments. Bedded cherts are conformable units within lacustrine sediments. Intrusive cherts include dykes and mound complexes of variable size. Many intrusions are capped by domal laminated cherts up to 30 cm thick. In thin section most cherts are composed of mosaics of finely crystalline quartz with patches of chalcedony. A few include carbonate components.

Bedded cherts

Bedded lacustrine cherts are present in exposed *Oloronga Beds* (~0.8 to 0.3 Ma), the *Green Beds* (100 to ~40 ka?) and the *High Magadi Beds* (~23 to 9 ka?). Nodular and lenticular cherts in the High Magadi Beds pass laterally into soft magadiite confirming a genetic link; some contain burrows. Bedded cherts in the fluvio-lacustrine Oloronga Beds are often deformed; some have reticulate surfaces similar to Magadi-type cherts, but their origin has not been studied.

The bedded quartzose cherts of the Green Beds, which cover the land surface around the south shorelines of Lake Magadi, resemble microbialites (Fig. 1A, B). They form beds, 1 to 4 cm thick, which cap zeolitic (erionite, analcime) lacustrine silts and fine sands; those silts have plant remains and vertical burrows >1 cm in diameter. The cherts are rippled or wavy laminated, implying shallow water. Some contain desiccation cracks, petee structures and locally abundant moulds of evaporite crystals (trona, gaylussite, calcite). In cross section laminae are recognised by changes in colour (grey, pale green, red) and crystal size.

Intrusive cherts

Reddish quartz cherts intrude bedded cherts and lacustrine silts, forming metre-scale dykes and domal mounds, commonly oriented along N-S faults and fractures (Fig. 1C–E). The mound and dyke cores are typically brecciated, but externally the mounds are covered by laminated chert, forming domal structures and complex large mounds locally >10 m across that resemble bioherms (Fig. 1E). The laminae commonly are arranged in repeating couplets or triplets. Mound surfaces are smooth and most lack desiccation features. Thick (>5 m)



massive cherts adjacent to fault scarps contain rare carbonate oncoids embedded in the quartz matrix.

Origins and implications

Unequivocal evidence for magadiite precursors (e.g. surface reticulation) is rare. Evidence for local carbonate replacement is present at a few sites, but is also rare. It is clear from many preserved structures (burrows, crystal pseudomorphs) that the precursor for the bedded chert was soft and probably gelatinous. Many features support an interpretation of formation on evaporative saline playa mudflats perhaps fed in part by silica-rich hot springs. Such environments are common at Magadi today. At a neighbouring lake, Nasikie Engida, soft silicate gels are forming along the shoreline near sites of hot spring inflow. Microbial mats cover and are included in some of those gels (Fig. 1E) together with microbial debris. The intrusive cherts show clear evidence of physical emplacement (brecciation) while partly solid and cementation by a fluid or gel. The mounds show little evidence of subaerial exposure and the external laminae probably formed subaqueously.

Many cherts at Magadi have laminae and structures similar to known or inferred microbialites in Archean rocks. Direct analogies are not implied here, but understanding genetic processes at Magadi might help to constrain the origins of some ancient silica microbialites. The cherts at Magadi do not appear to have formed constantly, implying temporal chemical-windows that favoured silica precipitation and diagenesis. As noted by Behr and Röhricht (2000), injection might have been linked to contemporary tectonics that allowed fluids and partly soft silica to migrate upwards along fault lines and fractures. Silica could have precipitated from alkaline fluids undergoing evapoconcentration or upon cooling of thermal fluids. Evidence for carbonate replacement is rare, but cannot be excluded in some locations.

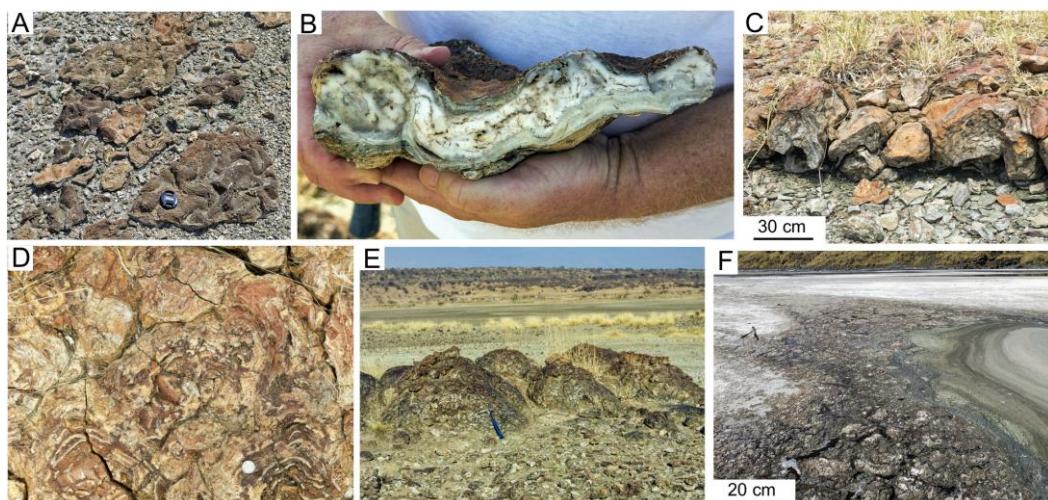


Figure 1. Examples of Green Beds chert at southern Lake Magadi, Kenya. **A.** Bedded cherts showing wrinkly surface. Lens cap: 50 mm. **B.** Bedded chert showing typical lamination. **C.** Domal laminated chert associated with intrusive mound; some small mounds are coniform. **D.** Laminated microbial? cherts capping intrusive mound. Coin for scale. **E.** Smooth domal chert mounds (internally laminated around margins, brecciated interior); hammer for scale. **F.** Modern Na-silicate gels (> 5 cm thick) covered by

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microbial mats, northern shoreline of Nasikie Engida, a hot-spring fed, saline alkaline lake.

References

- Behr, HJ (2002) Magadiite and Magadi chert: a critical analysis of the silica sediments in the Lake Magadi Basin, Kenya. *SEPM Spec Pub* 73, 257-273.
- Behr, HJ and Röhricht, (2000) Record of seismotectonic events in siliceous cyanobacterial sediments (Magadi cherts), Lake Magadi, Kenya. *Int J Earth Sci* 89, 268-283.
- Eugster, HP (1969) Inorganic bedded cherts from the Magadi area, Kenya. *Contrib Mineral Petro* 22, 1-31.



NOTES



Biofilms and Sediment: a ‘Geobiological Tango’

Christophe Dupraz

Stockholm University

The biosphere-lithosphere interface is the witness of an intimate ‘geobiological dance’ between the microbial community and the mineral world, orchestrating major element cycles on Earth. Environmental conditions are setting the stage for the development of communities, which in turn alters the environment through their metabolism. This feedback mechanism controls the characteristic mineral and organic products of a particular system and translates into the production of cells and extracellular organic matter (EOM), the trapping and binding of sediment, and the passive or active precipitation of minerals. These processes eventually lead to the formation of a model system for these interactions, a biofilm, or its more complex and organized form, a microbial mat.

Microbes are key players in the carbon cycling, influencing the balance between the more reduced and the more oxidized forms of carbon through their metabolic activities. Photosynthesis providing with the organic carbon that will then be ‘respired’ by bacteria using oxygen (aerobic) or other oxidized inorganic compounds (anaerobic) as electron acceptors. These metabolic activities are linking all major element cycling together (e.g., C, O, S, N, Fe, As) and are at the very core of the geomicrobiology and geobiology.

Microbial mats and biofilms are known to help the stabilisation of sediment, the preservation of sedimentary structure (microbially-induced sedimentary structure - MISS), and the fossilization of soft-bodied organisms through taphonomic processes. They can also produce organominerals, which represent minerals precipitated by interactions with the organic matter without enzymatic control. The precipitation in particular of carbonate organominerals is a fundamental piece of the carbon cycle and depends on two key components: the “carbonate alkalinity engine” and the extracellular organic matter (EOM). The alkalinity engine influences the mineral saturation index and can be ‘intrinsic’ when bacterial metabolisms affect supersaturation or lower the kinetic barrier of precipitation or ‘extrinsic’ when the physicochemical environment is forcing mineral formation. The organic matrix, which can be produced by various microbes within the biofilm, provides a template for carbonate nucleation and is known to influence morphology and mineralogy of minerals through cation binding. When preserved in deep time, this fossil microbial archive has the potential to give insight, among other things, into Earth earlier history and its redox revolution.



NOTES



The ‘sediment dilemma’ in fossil microbialites: Answers from a Lower Cretaceous microbial paradise

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‘Trapping and binding’ of sediment by microbial mats was first described in modern examples of Bahamas and was later popularized by the discovery of the Shark Bay stromatolites in Australia in the 70s. The idea that this was the most common accretion process in stromatolites became so widespread that soon some researchers warned and argued against what they called the ‘trapping and binding paradigm’, only based in modern examples. Few fossil agglutinated microbialites (almost exclusively formed by trapping and binding of surrounding sediment) have been described yet, a fact that has been dubbed ‘the sediment dilemma’. In the last years, this dilemma has gotten significant attention, and the deposits presented here provide a significant step forward in its understanding, since they have a remarkable abundance and diversity of microbialites, with varied and well-preserved microstructures, including some that were formed by trapping and binding and others that were not (Fig. 1).

The Leza Fm is a Lower Cretaceous unit (La Rioja, Spain), which through detailed sedimentological analysis has been interpreted as deposited in a complex system of coastal wetlands with variable fresh- and seawater influence. This setting favoured the development of diverse and contrasting microbialites (Fig. 1) in several different but laterally and vertically-related sedimentary environments: a) *Oncoids* were very common in small channels and water bodies with strong freshwater influence. They have microfabrics dominated by calcified filaments. b) *Skeletal stromatolites*, with strongly-calcified filamentous microfabrics, developed in shallow freshwater bodies with clastic input. c) *Agglutinated stromatolites*, with microfabrics dominated by trapped grains and clotted-peloidal micrite, occurred in tide-influenced near-marine salinity water bodies. d) *Micritic-evaporitic stromatolites* developed in restricted evaporative areas and they show micritic textures with abundant pseudomorphs after sulphates. e) *Thrombolites* occurred in water bodies with slight marine influence and show clotted meso- and microstructures. f) *Fenestral laminites* developed in shallow water bodies with strong marine influence and show undulose lamination marked by elongate fenestrae, and micritic, clotted-peloidal or agglutinated microfabrics.

A clear link is observed between each microbialite type and a specific environment of the system, indicating an important environmental control on microbialite development. The same macro- and mesostructures may occur in different environments (e.g. domal stromatolites), but microstructures are those that show a stronger environmental control. For example, filamentous microfabrics developed preferentially in freshwater-dominated facies, whereas agglutinated microfabrics occurred in shallow-marine areas, especially those with tidal influence. The main constraint for ‘trapping and binding’ is, of course, the presence of grains to be trapped, but in the Leza Fm, some microbialites with filamentous microstructures (i.e. oncoids and skeletal stromatolites) were surrounded by abundant grains and yet they were not significantly trapped within them. Thus, questions are raised: How are the grains delivered onto the microbial mats? How do they get stuck to them? The Leza Fm shows that, whereas biotic processes in mats obviously influence their development, environmental factors such as hydrodynamics (e.g. currents, tides) and hydrochemistry (e.g. carbonate saturation, salinity) may have a crucial role in the relationship between mats and sediment,



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influencing the type of microfabric in which a microbial mat is preserved in the geological record.

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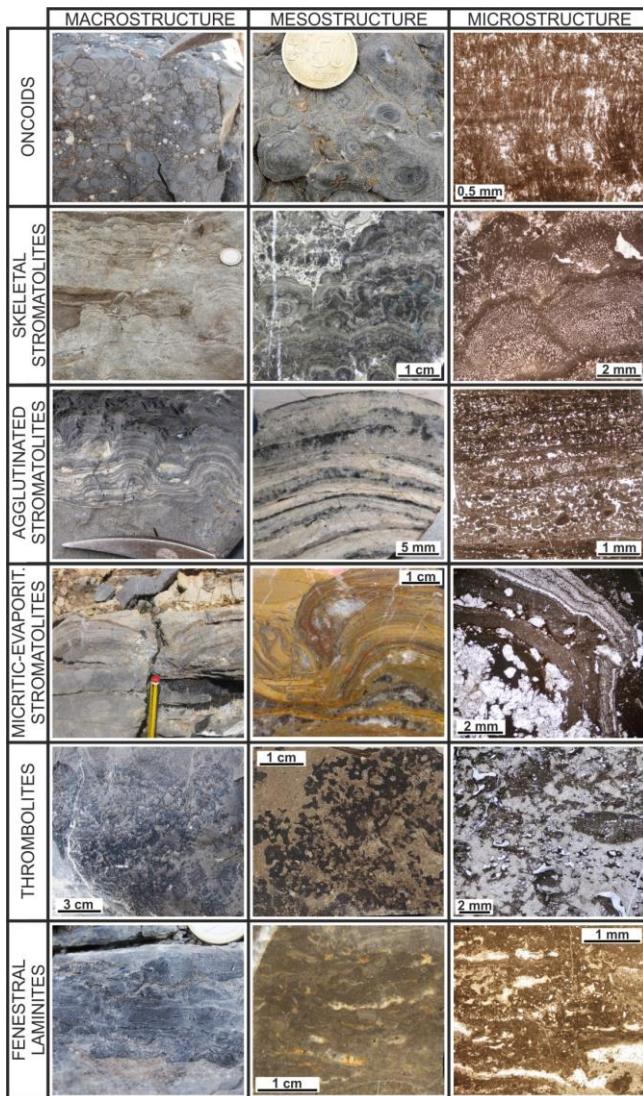


Figure 1: Different macro-, meso- and microstructures of the Leza Fm microbialites

NOTES

Microbes and the phosphatic cementation of heavy-element-rich oil shale in the Green River Formation (Eocene) of Utah, USA

Alexander Ani and Dave Keighley

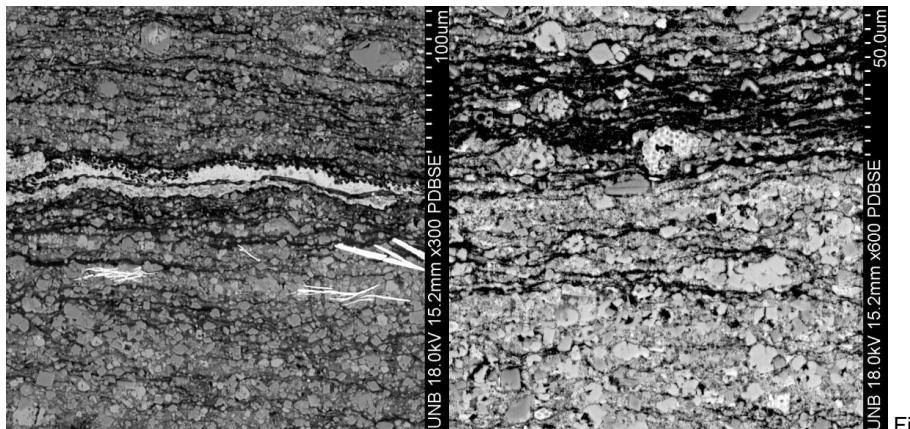
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It is well established that a major constituent of many organic-rich mudrocks (oil shales *sensu lato*) is detritus of microbial origin (e.g., cyanobacteria), and that microbes (e.g., methanogenic archaea) can also play a major role in the breakdown of the detritus. Less well understood is how substrate microbial communities influence pore-water geochemistry, lithify fine-grained sediment, and sequester variably toxic heavy elements. Oil shale sampled from the Green River Formation (GRF) is improving this understanding.

The GRF is a > 2 km-thick succession of fine grained strata, variably rich in carbonate, tuffaceous and organic material that accumulated in several lacustrine basins during the Eocene. In the Uinta and Piceance Creek basins of Utah and Colorado, the GRF hosts the world's largest oil shale resource. This resource is concentrated in 8 organic-rich intervals (upsection from R1 to R8), the richest being R7, also known as the Mahogany Oil Shale Zone (MOSZ) that marks the base of the informal upper member of the GRF. Ongoing studies relate to several beds of oil shale sampled from the lower R8 zone, ~60 to 130 m above the base MOSZ, both from core and outcrop.

Organic geochemical analyses suggest a stratified lake with tiers of planktonic algae, nitrate and sulfate reducing bacteria and deep water or substrate methanogens. Inorganic geochemical analyses indicate that most of the sampled oil shales contain phosphatic intervals, specifically of microcrystalline carbonate fluorapatite (CFA), which post-dated rhombic dolomite diagenesis, and mostly forms as a porous matrix to the rock. CFA in these intervals also occurs as other phases, including blocky pore-filling cement beneath and between carbon-rich (kerogenous) stringers, and microcrystalline masses arranged in clusters of globular structures (Fig. 1, 2). The blocky CFA contains nanometre-sized inclusions containing native or methyl Hg. The globular structures, where occurring in strata with abundant carbon-rich stringers, are enriched in W, also of uncertain mineralogy. The phosphatic intervals overall generally display upper and lower margins enriched in lanthanides and actinides that persist across over 2 km of outcrop.



Figs 1,2

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The blocky CFA likely resulted from the build-up of dissolved porewater phosphate sourced from decaying organics. As the phosphate diffused up toward the sediment surface, microbial mats (prior to their own death and decay) formed permeability barriers that retarded the diffusion, leading to supersaturation of the dissolved phase and CFA precipitation that also entrapped Hg present in the pores. The globular structures are interpreted to be of biogenic origin, most likely (facultative-) W-metabolizing sulfur bacteria or methanogenic archaea that inhabited the anoxic sediment before being rapidly fossilized by a phosphatization episode. Increased porewater phosphate is known to result from release of stored P by some marine bacteria under environmental stress, and a similar lacustrine environmental stress might also have been a factor in microbial phosphate release in the GRF sediment. In both these cases, and in other phosphatic oil shale beds of the GRF, as the microcrystalline matrix CFA crystallized, porewater lanthanides and actinides diffused partway into the phosphatic interval and substituted for Ca in the CFA lattice.



NOTES



Microbial mat ecology in lacustrine settings at the Meso-Neoproterozoic boundary

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Phosphatic nodules from the Torridonian Sequence in the Northwest Scottish Highlands preserve 3D snapshots of fossiliferous lacustrine sediments that include a range of microbially induced sedimentary structures (MISS). Thin sections cut vertically through MISS reveal organic laminae with a varve-like consistency within a very immature clay and silt matrix. Bedding plane parallel sections within phosphate may contain well preserved petrified cells and cell clusters, most of which appear to be eukaryotic protists, including encysted remains. Fragments of individual sheaths (e.g. *Siphonophycus robustum* Schopf) are present only as scattered, unoriented tubes (sheaths) lying within bedding planes, not as vertically-aligned, Oscillactoriacean sheaths. The only other common prokaryote is the recently described, *Eohalothece lacustrinus* Strother & Wellman, a small chroococccean whose elliptical cells are scattered throughout the organic-rich laminae. In rare instances entire populations of these cells appear to be *in situ*, but the individual cells themselves do not appear to be intimately involved in the trapping of sediment.

The dark shales that dominate the geologic section at Lower Diabaig, are riddled with a variety of finely textured surfaces that we now recognize as MISS. The most distinctive form is a reticulate mat whose counterpart has often been referred to as “elephant skin.” These sedimentary features were originally described as raindrop impressions, and, indeed, *bone fide* raindrop impressions have been found elsewhere in the Torridonian in finer grained red beds. At Lower Diabaig, microbial mat fabrics are sometimes crosscut by infilled desiccation cracks, and the same features may also overtop infilled cracks. This indicates that these microbial mats originally accumulated on sediments that periodically experienced subaerial exposure. Exceptional preservation of microbial populations within these mat-forming environments, in combination with palynological studies, enable us to build a new biosedimentary model in which the extracellular polymeric substances (EPS) associated with benthic biofilms becomes the binding agent for MISS production. This differs from carbonate-rich stromatolite-building ecosystems where sediment trapping is associated with motile filamentous cyanobacteria. Here, reticulated fabrics occur when surface biofilms were exposed to precipitation. Subsequent rapid burial by angular silt grains allowed for the retention and preservation of the primary microbial fabric. Intriguingly, both raindrop impressions and similar reticulated patterns can be found today in the northwest Scottish Highlands in the algal slime growing on stream banks just after rain and sleet have fallen.



NOTES



Microbial activity as a key control on fluvial-aeolian landscapes in the Cambrian

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Detailed analyses of planar sedimentary strata in cores from the Cambrian Mount Simon Sandstone, IL, USA, indicate the importance of deflation of exposed dry sand by wind, and adhesion of sediment when the ground surface is wet. Moreover, crinkly planar strata that are interpreted as biofilms at the soil surface are abundant. These irregularly-shaped, undular, laminae formed in fine to medium sands are 1-5 mm thick, have amplitudes in the order of 2-10 mm, are lined with silt, clay and micro-crystalline iron-oxides, and appear filamentous or layered in cross-section. Signs of surface hardening during desiccation are common, such as the local presence of conformably-overlying windblown sand in areas sheltered by small surface elevations and breaks in the planar laminae that likely represent shrinkage cracks. Intraclasts of the fine-grained laminae and a few potential roll-up structures were also observed.

Before the development of land vegetation, floodplains with biofilms on their surface would have been exposed frequently to the wind. These thin regoliths with biofilms have the potential to cement the surface and therefore fundamentally change the way in which sediment was stored on, and released from, such floodplains. Surface cementation would likely retain sediment within the floodplain deposits, and therefore potentially change the availability of sediment for the construction of desert dunes. Systematically localized deflation and adhesion, related to the position of the groundwater table, has the potential to change the super-elevation of alluvial channels relative to their surrounding floodplains and, as a consequence, the potential for avulsions. When integrated over millions of years, the interplay between wind, groundwater, and surface cementation also has the potential to change the delivery of sediment to the oceans by wind, as well as the proportion of fines that remains within terrestrial deposits.

These findings and speculations have far-reaching implications for landscape development and the construction of the sedimentary record during the Cambrian and Precambrian. The recognition of biofilms, and the timescales of their construction and disintegration, are thus pivotal to interpret the development of alluvial and coastal systems before vegetation developed on land.



NOTES



Microbial mats as agents in the formation of discoidal pseudofossils: observations from the Ediacaran Longmyndian Supergroup, Shropshire, England

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Microbial mats are thought to have been ubiquitous in the Ediacaran Period, and microbial colonies have been proposed to explain some of the discoidal impressions that dominate assemblages of the enigmatic Ediacaran biota. We here present evidence that a suite of small (~0.5–5 mm diameter) discoidal markings, some with simple ornamentation, on bed soles and tops of Ediacaran rocks of the Long Mynd, previously interpreted as representing a depauperate Ediacaran assemblage, can be fully explained by the action of microbial mats on sediments, operating in conjunction with physical processes.

We examined discoidal markings on rocks of the upper Burway Formation of the Ediacaran Stretton Shale Group, Longmyndian Supergroup, Shropshire, England, first described by John Salter in 1856 (Fig. 1A). Their biogenicity was later debated but they were interpreted more recently as body and trace fossils of Ediacaran organisms. Submillimetric laminae of strongly colour-contrasted mudstone and fine sandstone in the upper Burway Formation provide an exceptional window on small-scale sedimentary structures in cross-section. The laminae are punctuated by distinct white layers found to be silicified microbial mats, showing well-preserved filaments (Fig. 1C).

Systematic grinding through discoidal markings on bed tops and soles reveals sandstone fills and irregular submillimetric vertical columns (Fig. 1B), associated with microbial mat layers, as well as disrupted mudstone laminae. We interpret the sandstone columns as very small scale fluid escape, driven in part by overpressure exacerbated by the sealing effect of microbial mats. This process, together with different patterns of sediment injection and loading at matground surfaces, is sufficient to explain discoidal impressions on bed soles and tops previously ascribed to the Ediacaran taxa *Medusinites* and *Beltanelliformis*. Incomplete raised rings preserved in positive relief on both bed soles and tops, previously ascribed to the trace fossil *Intrites*, are revealed through grinding to be torus-shaped, filled with pale, very fine grained sediment, and associated with a central sandstone column (Fig. 1D). We interpret these “*Intrites*-like structures” as a form of microstromatolite (MISS), resulting from microbial trapping and binding of sediment, possibly with some microbially mediated clay mineral precipitation, on the raised flanks of sediment volcanoes.

Our study demonstrates the range of microbial-matground-associated structures that result from the interaction of physical processes and microbially bound surfaces – structures that may be mistaken for body and trace fossils. This urges reconsideration of similar suites of discoidal markings used to support claims of depauperate Ediacaran biotas worldwide.

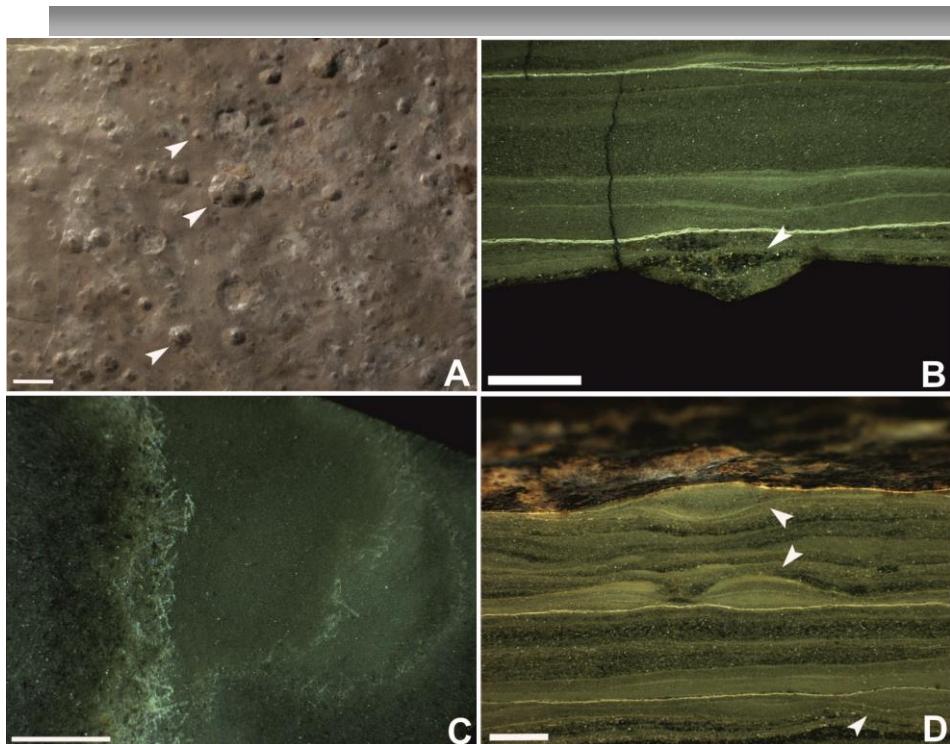


Figure 1(A-D): Surface appearance and cross-sectional views of Longmyndian discoidal forms. **A:** Bed sole with pimple-like mounds, mounds with central bosses (formerly described as *Medusinites*), and mounds with boss and lobes (typical examples arrowed). **B:** A “*Medusinites*” disc in cross-section. Note thick white microbial mat layers, and widening central sandstone feature (arrowed). **C:** Silicified microbial filaments forming mat layers visible on ground top surface of hand specimen. **D:** Examples of *Intrites*-like structures in cross-section (arrowed), with both lobes visible in central example, a microbial mat below, and dark sandstone visible between the lobes. Scale bars: A: 5 mm; B–D: 1 mm.

NOTES



Microbialite mounds of the Mupe Member of the Purbeck Limestone Group (Upper Jurassic), Dorset, southern England.

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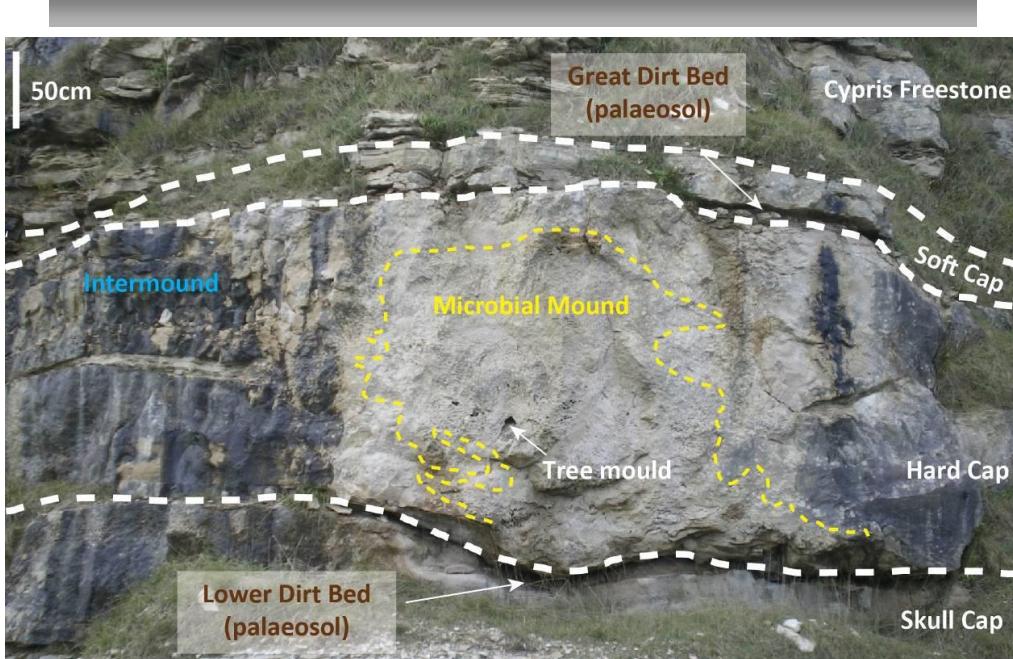
Microbialites are classified based on their internal structures or the processes involved in the microbial growth. However little is known on the impact of the environment (climate, hydrology and water depth) or microbial processes on the preserved internal structures. This limits their use as palaeoenvironmental indicators and in sedimentological analyses. This study is developing new depositional reconstructions for non-marine brackish water microbialites in a semi-arid climate setting based on the Purbeck Limestone Group (Upper Jurassic – Lower Cretaceous) exposed in Dorset (southern England, U.K.).

Outcrop study and remote sensing imaging (lidar) coupled with petrographic study is used to differentiate microbialite mounds and bedded inter-mound packstones-grainstones areas and to characterise four facies. Petrography and MicroCT scanning are used as a proxy for porosity and permeability and to classify the different pore types. These are integrated to illustrate the sequence of possible events and processes involved in the formation of the microbialite mounds.

Particular attention focusses on the lower part of the Purbeck limestones characterised by the accumulation of *in-situ* microbialite mounds (up to 4m high and 20m across) that occur within bedded, inter-mound peloidal packstones-grainstones. The microbialite mounds are located in three stratigraphic units ("Skull", "Hard" and "Soft Caps") separated by three palaeosols ("Basal", "Lower" and "Great Dirt Beds") respectively, within three shallowing-upward lacustrine sequences. The microbialite mounds reveal complex and irregular shapes (Fig.1) due to their association with tree remains and to inferred lake level fluctuations. Interpretation of high-resolution, ground-based lidar data collected from 7 quarries in the Isle of Portland enables a quantitative description of the morphology of the mounds and their relationship with tree remains and the inter-mound facies. The microbialite mounds are commonly constructed from more tabular shaped smaller mounds (up to 50cm high and 1m across) that comprise 3 sub-facies (Stromatolites, Thrombolites and Burrowed peloidal packstone). Many of these small-scale mounds developed around trees and branches which are preserved as moulds or silicified wood. The Burrowed peloidal packstone facies forms a microbially-bound casing around tree remains when the trees were still in an upright position. Contemporaneously, the Stromatolite facies was locally deposited on the lake floor. This sequence of events is also confirmed by the re-orientation of geopetal sediments with that infilled burrows. Subsequently, the Thrombolite framework, that constitutes the main mound-building facies, developed preferentially on the upper part of fallen trees. This helps to determine that the preserved filamentous cyanobacteria were phototactic and grew in shallow waters. The inter-mound facies shows horizontal stratification onlapping and interfingering with the mounds (Fig.1) that suggest that the deposition occurred during the development of the thrombolite framework. Initial work on the pore system suggests these microbialite mounds present high framework porosity and relatively good permeability; while inter-mound facies shows moderate intergranular porosity and relatively poor permeability.



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NOTES



**Hydrochemistry and biofilm calcification in tufa canal-forming karstic streams
("Steinerne Rinnen", Southern Germany)**

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Calcium carbonate precipitation and tufa formation in karstic streams are commonly attributed to CO₂ degassing and associated rise in pH and calcite supersaturation. On the other hand, microsensor measurements have demonstrated that, wherever biofilms are present, photosynthesis controls benthic calcification in a diurnal cycle. However, the relative importance of inorganic versus biological impact on the carbonate equilibrium apparently varies between different tufa-forming settings. While in most cases tufa deposition occurs as laminated veneers of stream beds, small dams and cascades, few sites are known with so-called „Steinerne Rinnen“ (Fig. 1). These are aqueduct-like tufa-canals up to 5 m high and 185 m long with a narrow water streamlet on their top. The formation of the „Steinerne Rinnen“ has been attributed to CO₂ degassing of the karstic water, enhanced at a morphological terrain edge, and subsequent canalization by calcite-encrusted mosses. In the present study, six „Steinerne Rinnen“ and one subterranean karstic stream have been investigated from their springs downstream to the end of the tufa deposits with respect to their hydrochemistry and biofilm calcification in comparison with other tufa-forming streams in Germany. As a result, the „Steinerne Rinnen“, which are dominated by inorganically driven calcification, reach downstream much lower calcite supersaturation if compared to karstic streams dominated by biofilm photosynthesis-controlled calcification. The subterranean karstic stream, with only few microbial cells present, shows lowest maximum calcite supersaturation. A positive correlation between calcite saturation and ions interfering with calcite nucleation and crystal growth („inhibitors“) is evident for surface streams. In the subterranean stream, a low calcite saturation index has been observed despite of moderately high inorganic inhibitor concentrations. This observation is explained by the almost complete lack of benthic microbial cells and hence absence of inhibiting biofilm exopolymers in this dark environment. In conclusion, the results suggest that the higher the inhibition, the higher the biological control on calcification. Inhibition of calcite precipitation resulting in higher supersaturation is caused either by inorganic ions (Mg²⁺, SO₄²⁻, PO₄³⁻) and/or by biofilm exopolymers.



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Fig. 1. The tufa canal "Steinerne Rinne Erasbach" in autumn 1992 (left) and 2006 (right).

NOTES



Microbially driven carbonate chimney construction at Mono Lake, California

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Mono Lake, California, is renowned for its 20th century to Pleistocene vegetation-encrusted tufa mounds and boulder-encrusting tufa sheets. Competing geochemical and geobiological models have tried to explain tufa precipitation in the lake. In the geochemically-driven models, calcium carbonate precipitation was caused by mixing of highly alkaline, high pH lake water with Ca-rich spring water that emerges along fault lines from beneath the lake. On the geobiological side are observations of microbes or algae at sites of active tufa growth that were inferred to have influenced carbonate rock deposition. In these 'geobiological' models metre-scale chimney construction might be attributed to development of microbial biofilms around spring vents, and so chimney morphologies may reflect presence of fossil microbial life. Here we report results of a high-resolution petrographic and geochemical study that aimed to determine whether microbes controlled construction of c. 3 to 4 m high 'chimney' structures. Internally the chimneys are constructed of stacks of numerous calcitic cones or pipes, each 30 to 60 cm in height and around 3 cm in width. Each pipe has a central 1 cm-sized void or conduit. Clusters of dark coloured filaments observed in thin-section using optical microscopes were found within the columnar to shrub-like calcite growths that make up the pipe walls. Coccoids were also found. NanoSIMS maps of carbon, nitrogen and silicon, combined with 3d reconstructions and SEM-EDS maps, reveal cellular structures surrounded by silicates. We will show these combined data and discuss relationships between the silicates and carbonates. We will present an up-dated model for microbially-mediated intracellular and extracellular carbonate precipitation in Mono Lake.



NOTES



Abiotic vs biotic-influenced carbonate nucleation: towards identifying their unique textural signatures

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Phase diagrams are extremely powerful interpretive tools for converting qualitative observations about a sediment into quantitative constraints on the environment in which it was deposited. We present a new phase diagram for growth forms in non-marine calcite sediments, showing the competing influence of the chemical “driving force” (saturation index) of the precipitating solution and the degree of interference with crystal growth from acidic organic additives. This powerful approach permits the identification of biogeochemical conditions within palaeo-environments from petrological criteria in much the same way analogous phase diagrams allow past flow conditions to be reconstructed from clastic bedforms.

The phase diagram approach is particularly powerful in environments where it is difficult to distinguish between carbonates grown by purely abiotic mechanisms and those nucleated under the influence of microbial activities, especially where both processes are acting simultaneously. Microbial organisms can control carbonate precipitation directly (bio-mediation), or indirectly by stimulating or influencing calcite crystal nucleation through the production of extracellular polymeric substances (bio-influence). Bio-influence has proven especially difficult to diagnose in past deposits, but particularly tractable to phase diagram approaches.

As with clastic bedform systems, where phase diagrams were first produced experimentally for non-cohesive sediments, we present a simplified case where calcite morphologies are produced experimentally from sterile solutions containing variable inorganic and organic phase concentration. Multiple complicating factors exist for both bedform (cohesive sediment, macrophyte colonization, bio-erosion) and growth form (Mg/Ca, flow hydraulics, metabolic processes) approaches, providing ready-made hypotheses for ongoing research. However, the new diagram already demonstrates conspicuous phase transitions which respond to a combination of changes in saturation index (SI) and organic acid concentration. Experimental treatments were prepared adjusting the CaCO₃ saturation state of the parental solution between pH 7 and 12. Similarly, the concentration of alginic acid was varied between 0, 0.01, 0.1, 0.5 and 1 mgL⁻¹.

SI increase drives a conspicuous calcite morphology change from anhedral-subhedral prismatic crystals to euhedral spherulitic crystal aggregates at higher pH (i.e. SI) (**Fig. 1**). Increased in alginic acid concentration reduces the pH (i.e. SI) at which this transition occurs, bringing it into the range observed in many naturally occurring sites (pH 7 to 10 rather than 11 to 12). Furthermore, a change from poorly developed trigonal to tetragonal prismatic calcite flat layers towards vertically stacked octahedrons and tetragonal calcite trapezohedrons was observed by increasing the organic acid content. A transition from tiny rhombic calcite crusts towards tightly packed calcitic spherulitic bodies, and then massive flat crusts of octahedrons-dodecahedron calcite crystals was recognised by increasing organic content at higher SI (pH>10). ‘Shrub’-like growth forms were observed only at higher alginic acid concentrations with extremely high saturation indexes. In our sterile experiments, the



lower limit of calcite occurrence is recognised at pH8 and heterogeneous concentrations of alginic acid (0.01 and 0.5 mg/L) implicating that specific metabolic thresholds are providing the activation energy needed for mineral formation. No calcite is observed at circum-neutral pH 7 which is dominated by amorphous silicate phases rich in K, Mg and Ca, and halite crystals (**Fig. 1**). The overall effects of increased organic contents in solution are enhanced aggregation of spheroidal particles forming spherulitic flat crusts and in some cases growth of positive 'shubby' carbonate morphologies.

Our novel approach provide an innovative framework to link specific petrographical assemblages with well-constrained biogeochemical conditions, shedding light onto the distinctive morphological signatures that abiotic and biotic-influenced mechanisms leave in carbonate crystals.

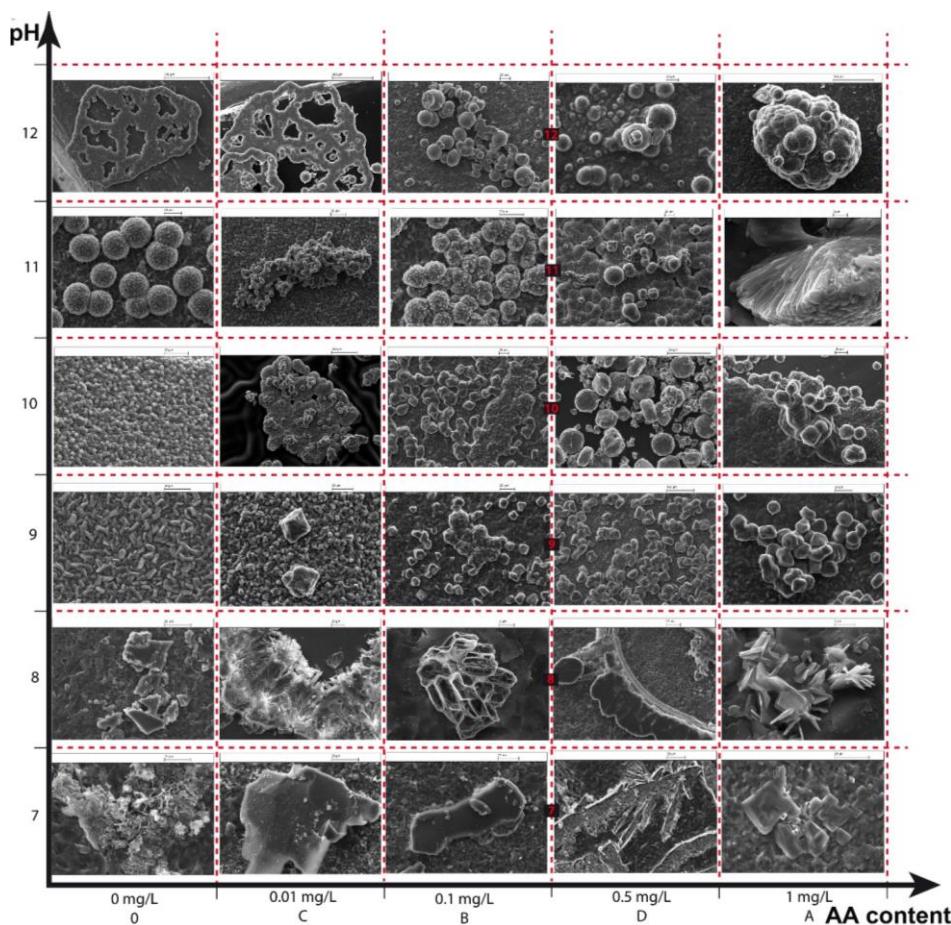


Fig. 1. Calcite/silicate morphologies grown under different saturation indexes (pH) and alginic acid contents (AA)

NOTES



Oxygenic and anoxygenic photosynthesis in a microbial mat from an anoxic and sulfidic spring.

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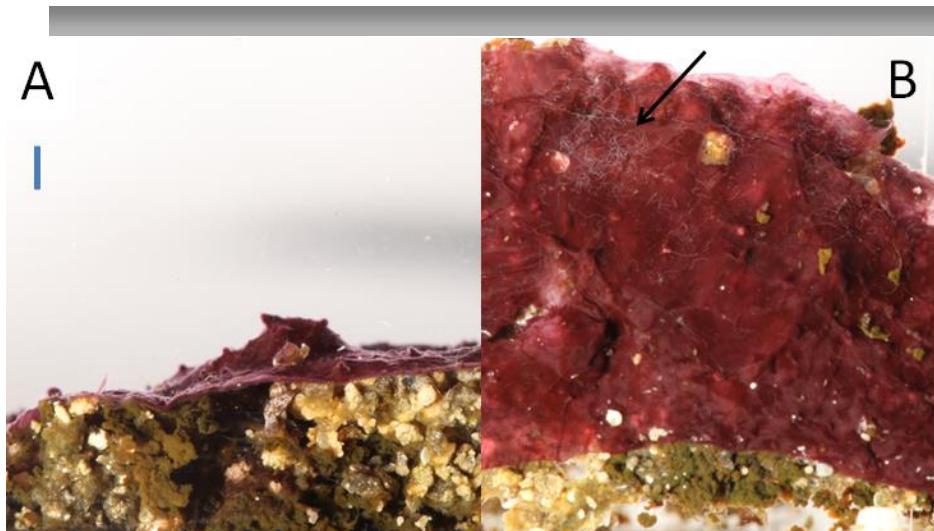
The Little Salt Spring sinkhole is an anoxic ecosystem that is used as analog for the Proterozoic world, before and during the great oxidation event. The lake is stratified and below 3 m depth anoxic and slightly sulfidic. At the lake bottom at 9 m depth, red cyanobacterial mats cover sediments full of green sulfur bacteria (GSB). Detailed microscopy revealed the community to be exclusively microbial. Previous community studies of the mat are complemented by this study of the biogeochemical processes. We aimed to find out if oxygenic photosynthesis could occur in this sulfidic environment and if oxygen export from the mats could occur. Oxygenic and anoxygenic photosynthesis rates were measured *in situ* and in the laboratory using microsensors. The combination of *in situ* and laboratory measurements complement physiological findings by molecular and culturing methods. We found evidence for direct transfer of radiation energy up to 1 cm deep in the mats, although the *in situ* quality and intensity of the radiation is unfavorable for photosynthesis.

In situ microsensor data showed both oxygenic photosynthesis in the red surface layer and light-induced sulfide dynamics up to 1 cm depth. Anoxygenic photosynthesis occurred during all daylight hours, with complete sulfide depletion around midday. Oxygenic photosynthesis was limited to 4 hours per day, due to sulfide inhibition in the early morning and late afternoon. Laboratory measurements on retrieved samples showed that oxygenic photosynthesis was fully but reversibly inhibited by sulfide.

We also found that iron cycling in such mats has a profound effect on photosynthesis. Fe(III) accumulated in the photic zone due to oxidation by light and then alleviated the inhibition of oxygenic photosynthesis by sulfide, and effectively inhibited anoxygenic photosynthesis. Oxygen evolution occurs in a layer less than 1 mm thick during 4 hours per day, yet this is enough to support aerobic microorganisms. This type of microbial ecosystem was possibly the first aerobic environment on early Earth, in which the biochemical tools were developed to survive and flourish in an oxygenated world.



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The mats consisted of a thin red layer (1-2 mm) on top of coarse sand, (A) imaged from the side, and (B) from above. The bar in the (A) panel is 5 mm. The pore space in the sand underneath was filled with green biomass, consisting of GSB. *Beggiatoa* (aerobic sulfide oxidisers) are visible in the upper area of the right panel as thin white filaments. The arrow points towards a particularly densely populated area.

NOTES



Modern and ancient biosignatures in sabkha-associated microbial mats

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Microbial mat ecosystems have been operating at the sediment-fluid interface for over 3400 million years, influencing the flux, transformation and preservation of carbon from the biosphere to the physical environment. These ecosystems are excellent recorders of rapid and profound changes in earth surface environments and biota as they often survive crisis-induced extreme paleoenvironmental conditions. Their biosignatures, captured in the preserved organic matter and the biominerals that form the microbialite rock, constitute a significant tool in understanding geobiological processes and the interactions of the microbial communities with sediments and with the prevailing physical chemical parameters, as well as the environmental conditions at a local and global scale. Nevertheless, the exact pathways of diagenetic organic matter transformation and early-lithification, essential for the accretion and preservation in the geological record as microbialites, are not well understood.

The Abu Dhabi coastal sabkha system contains a vast microbial mat belt that is dominated by continuous polygonal and internally-laminated microbial mats across the upper and middle intertidal zones. This modern system is believed to be the best analogue for the Upper Jurassic Arab Formation, which is both a prolific hydrocarbon reservoir and source rock facies in the United Arab Emirates and in neighbouring countries. In order to characterise the processes that lead to the formation of microbialites we investigated the modern and Jurassic system using a multidisciplinary approach, including growth of field-sampled microbial mats under controlled conditions in the laboratory and field-based analysis of microbial communities, mat mineralogy and organic biomarker analysis.

In this study, we focus on hydrocarbon biomarker data obtained from the surface of microbial mats actively growing in the intertidal zone of the modern system. By comparing these findings to data obtained from recently-buried, unlithified mats and fully lithified Jurassic mats we are able to identify those biochemical signatures of organic matter preserved in microbialites which survived diagenetic disintegration and represent the primary microbial production.

Biomarkers, in the form of alkanes, mono-, di- and trimethylalkanes (MMA, DMA, TMA) were identified in surface and buried mats. Previous studies reported a bimodal distribution of *n*-Alkanes in the buried mats due to the relatively rapid decline in the abundance of MMAs and DMAs in the C₁₆-C₂₂ range with C₂₄-C₄₅ exclusively found in buried mats, however, this bimodal distribution was not found in our samples. Furthermore, we were able to improve the subsurface facies model for the Jurassic microbialites with our biomarker data as it shows that microbial mats growing in tidal pools or lagoons within the sabkha system form the most prolific hydrocarbon source rocks.

NOTES



The combined effects of cyclic particle flux and anaerobic oxidation of methane support growth of a laminated seep bioherm off Pakistan (northern Arabian Sea)

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The chief controller of particle flux to the seabed in the northern Arabian Sea is the Indian monsoon. Monsoon-related strong winds and heavy rainfalls deliver nutrients to the surface waters, resulting in algal blooms during the summer and winter monsoon seasons and associated peak particle fluxes. Such particles get trapped and bound by benthic microbial mats at methane seeps within the oxygen minimum zone off Pakistan. At the same time, sulphate-dependent anaerobic oxidation of methane (AOM) induces precipitation of ¹³C-depleted aragonite cement at the seeps.

Here we show that cyclic sedimentation pulses related to the Indian monsoon in concert with precipitation of AOM-induced aragonite gave rise to a well-laminated, porous seep bioherm in 734 m water depth. U–Th dating indicates that the build-up grew during past ~1,130 years, revealing a relatively fast up-ward growth rate. Monsoon-controlled formation of authigenic seep-carbonates extends the known environmental processes recorded by this type of deposit. Our study introduces a deep-water stromatolite that results from the interaction of atmospheric and seabed processes.

NOTES



Not just along for the ride – the influence of extracellular polymeric substances on fine-grained sediment gravity flows

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Sediment gravity flows are one of the most significant processes by which sediment is transported from the continent into the deep ocean. Our current understanding has been formed from over 60 years of multi-disciplinary research on the flow mechanics and deposits of submarine saline density currents and sediment gravity flows. Over the last two decades, studies have shown the electrochemical forces between clay particles can induce significant changes in the flow rheology of fine-grained sediment gravity flows, common in the deep marine environment. Flocculated clay particles can enhance or dampen turbulent forces in sediment gravity flows such that as the cohesive sediment content increases, the flow transitions from turbulent Newtonian flow, via transient-turbulent flow, to laminar non-Newtonian debris flow. Different rheology exhibit different depositional styles and a comprehensive understanding of the effects of cohesive particles within these flows is critical for our interpretation of the architecture and the palaeo-environment setting of their deposits.

In the natural environment, clay-rich sediments are commonly associated with the presence of organic matter. Shallow marine ecosystems frequently support populations of algae assemblages, dominated by diatoms that are estimated to produce approximately 40% of the total global primary productive in marine systems. These diatoms form 'biofilms' on the sediment surface, composed of matrix sediment, cells and 'sticky' extracellular polymeric substances (EPS). Within shallow marine sedimentary deposits, the presence of EPS encourages the flocculation of clay and increases the stability of the bed by bonding with the sedimentary particles, an effect stronger than the physical cohesion by clays. But EPS's impact on sediment transport processes has not been explored yet. Here, the influence of similar interactions for suspended clay and EPS within sediment gravity flows is presented.

The above research gaps were addressed by means of flume experiments that recorded changes in dynamic behaviour and deposit run out distances of sediment gravity flows with variable amounts of xanthan gum (a commonly used proxy for natural EPS) and physically cohesive kaolin clay (one of the most common clay minerals on Earth) and non-cohesive silica flour. Results indicate that very small quantities of EPS – three orders of magnitude smaller than the quantity of clay – are sufficient to enhance flocculation and alter the size distribution of clay flocs compared to a flow that lacks EPS. Ultrasonic Doppler Velocity data demonstrate changes in the internal turbulence behaviour of transitional flows as a result of adding EPS. These findings demonstrate the importance and capability of biological processes in sedimentological transport processes and have the potential to change our understanding of sediment gravity flows in the natural environment.



NOTES



Subaqueous sedimentary cracks: evidence for a microbial contribution

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The rock record shows that diverse subaqueous sediments have cracked at or below the sediment–water interface (SWI) in marine and lacustrine settings throughout Earth history. Although the resulting features may resemble filled desiccation cracks, subaerial exposure can be confidently ruled out in many cases, and it is clear that many cracks opened centimetres below the SWI. It is well known that salinity fluctuation can drive crack formation by synaeresis in swelling clays, but this mechanism is not appropriate to explain cracks in other substrates and in palaeoenvironments where salinity fluctuation is implausible. A number of alternative explanations have been offered; while none of these is universally applicable, each may be correct in respect of particular sets of cracks in the rock record.

Recent attention has focused on the role of microbial activity, either in providing the cohesion that allows sediment to crack underwater (by sticking grains together with EPS and producing bubbles that entrain and remove porewater), or in disrupting the cohesive sediment to produce cracks (for example, by making the sediment heterogeneously resistant to compaction, by emitting gas, or by inducing bulk volume change through the decay of biomass). Clear geological evidence for a microbial role in subaqueous cracking is provided by sinuous ripple-trough cracks ("Manchuriophycus") and branching spindle cracks in clay-poor marine sandstones, whose grains would not have behaved cohesively unless they were bound together by biofilms. Good examples are found in the Ediacara Member of the Rawnsley Quartzite (Australia; Gehling 2000) and in the Acacus Formation in the Silurian of Libya (Pflüger 1999). In these and other rocks, some cracks are associated with microbially induced sedimentary structures. Harazim et al. (2013) have also reported textural and carbon-isotopic evidence for an association between microbial productivity and crack occurrence in mudstone in the Ordovician Beach Formation of Newfoundland.

We investigated several proposed mechanisms of subaqueous crack formation in the laboratory (McMahon et al. 2016). In one set of experiments, plugs of organic-rich tidal mud capped with thick microbial mats were extracted from a natural saltmarsh and placed in transparent vessels with seawater. The change in environment caused the microbially fertile mud to produce copious pungent gas over the following weeks, which left snaking voids that were passively filled from above. These voids somewhat resembled the planar, interconnected methane-filled vacancies previously discovered 10s of cms below the SWI in the Baltic Sea, which are a promising analogue for ancient subaqueous sedimentary cracks (Abegg & Anderson, 1997; Furniss et al. 1998). In some vessels, hairline fractures also developed between these voids.

We discovered additional evidence of microbially induced cracking serendipitously in our laboratory. A green microbial mat developed spontaneously in a jar of kaolinite and distilled water. For unknown reasons, the undisturbed mat spontaneously formed small radiating shrinkage cracks at the centre of the vessel over the following several days (**Figure 1**). To our knowledge, this is the first time that bacteria have been directly observed to mediate the formation of subaqueous sedimentary cracks. Further work is warranted to provide a better understanding of this phenomenon and its relevance to the geological record. Ultimately, a

fuller understanding of subaqueous sedimentary cracks may yield insights into the rheological and biogeochemical evolution of sediments through time.

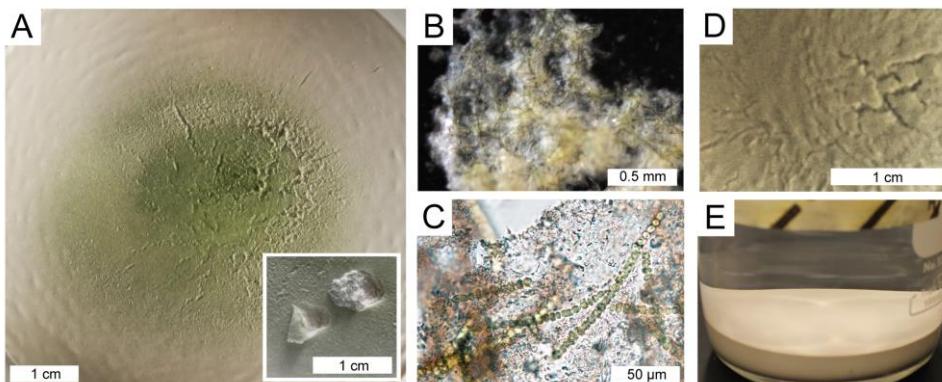


Figure 1 Cracks at the sediment-water interface in vitro. **A:** Plan view showing greenish microbial mat on kaolinite (60g) in distilled water (100 ml). **Inset:** The mat was strong enough to peel back with tweezers from the underlying sediment. **B, C:** Microscopy reveals kaolinite grains interwoven with *Anabaena*-like cyanobacterial filaments. **D:** The experiment produced the same result when subsequently repeated under identical conditions, indicating that the clay stock was probably contaminated. **E:** a sterile (autoclaved) control did not develop either a cohesive surface, cracks, or any other features.

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NOTES



Implications of cyanobacterial response to rainfall for dryland stability

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Dryland soils can be highly susceptible to wind erosion due to low vegetation cover. However, cyanobacteria in soils between sparse vascular plants can exert some control on surface erodibility by binding individual sediment particles together to form aggregates, and/or by creating a protective organic web over the surface (Figure 1).



Figure 1: Extracellular polysaccharide (EPS) binds particles together.

The development of these cyanobacterial soil 'crusts' is highly dependent on rainfall or flooding that triggers photosynthetic activity and an increase soil organic matter within biological soil crusts. Rainfall also causes sediment compaction and aggregate breakdown to form physical soil crusts and differentiating the impact of physical and biological crusts on landscape stabilisation is difficult.

Using controlled field experiments, this study tests how biological soil crusts in different dryland geomorphic settings (Figure 2) respond to various rainfall amounts (0, 5 or 10 mm) and how this in turn affects the resistance of soils to wind erosion.

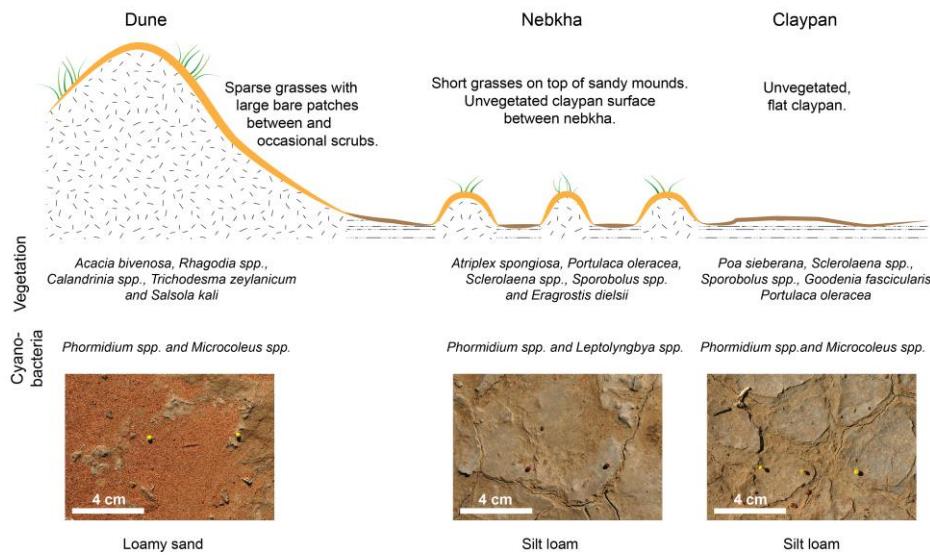


Figure 2: Field sites in Queensland, Australia along a transition from an aeolian-
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dominated sedimentary environment (dune) via a transition area of nebkha dunes to a flood-dominated sedimentary environment (claypan).

Results show that 10 mm of rainfall triggers more intense photosynthetic activity (high fluorescence) and typically a greater increase in chlorophyll *a* and extracellular polysaccharide content in biological crusts than 5 mm of rainfall, but that the duration of photosynthetic activity is comparable for both quantities of rain (Figure 3). The biological response of the cyanobacteria to rainfall has a strong, positive relationship with air temperature i.e. higher values and more sustained fluorescence at warmer temperatures.

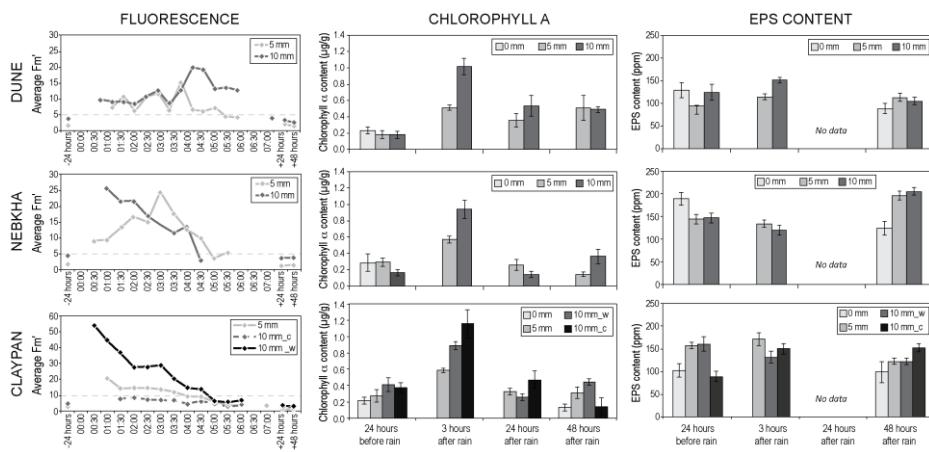


Figure 3: Biological indicators of cyanobacterial response to different rainfall amounts at the three sites.

There is some evidence to suggest that although cyanobacterial activity increases the surface strength of soils, the overall surface susceptibility to wind erosion is increased following the rainfall events. This may be due to the physical impact of raindrops detaching particles from the surface crust and making them available for wind entrainment. This suggests cyanobacterial growth facilitated by direct, high energy, raindrop impact may be less effective at stabilising soils than that facilitated by indirect, low energy flooding.

NOTES



Microbially-influenced Architectural Preservation in Aeolian Bedforms

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We suggest that bio-diagenetic processes can preserve aeolian landforms complete with internal dune architecture. In the Wahiba (or A'Sharqiyah) Sand Sea of Oman, landform and outcrop evidence, candidate bio-geophysical attributes and an Environmental Scanning Electron Microscope (ESEM) investigation all suggest that microbes may stabilise and preserve the draa with full sets of internal depositional features. If so, the draa may be comparable with those stromatolites in which microbial mats trap and bind sediment. Dry, mobile seifs migrate over sparsely vegetated whalebacks of ancient draa; much as sand waves wash over sub-tidal stromatolites.

Whereas Rotliegend reservoirs mostly comprise the bottom sets of mobile dunes between closely spaced growth surfaces, the static draa of the Wahiba preserve entire buried seif dunes. Within the draa, Ground Penetrating Radar (GPR) profiles and volumes show complete suites of seif bedforms, up to and including abundant crestal ridges. The buried seif dunes accrete along deeper, rounded ridges – a relationship seen in the modern landscape.

Abrupt changes in moisture levels define Radar Stratigraphic Units (RSU). Within each RSU, moisture and relative dielectric impedance increase downwards as radar velocity decreases, whilst conductivity remains roughly constant. Most reflection event signatures imply sharp damp-over-dry interfaces between RSUs and long-term stability – despite being far from diffusional equilibrium. Microbial hydrophobins are a candidate cause of long-term soil water repellency for such a bio-geophysical signal. Euhedral calcite, sodium and potassium-bearing feldspar crystals overlay thin, rimming calcite and clay cements, some rich in iron and titanium.

The Magnetic Susceptibility profiles are independent of moisture, relative dielectric impedance and conductivity, decreasing uniformly downwards across the sharp RSU boundary. That suggests vertical, reductive chemical gradients that are insensitive to moisture levels, perhaps due to microbial communities.

We also note dimmed or radar-transparent patches deep within some of our 250 MHz 3D-GPR volumes, long 30 MHz Ultra GPR profiles and also in a published GPR profile from Namibia. The underlying reflection events retain their amplitudes beneath the dimmed or semi-transparent geobodies, which rules out a local increase in conductivity with signal loss below. Perhaps the moisture contrasts that delineate original bedforms in the GPR are locally elided; hydrophobins can reverse surface wettability at critical soil moisture content.

NOTES



Microbial transport and soil integrity in drylands

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Dryland soils are particularly vulnerable to erosion because of low plant cover and low organic matter which is linked with water availability and biological constraints. It is increasingly recognised that dryland soils can be managed to minimise erosion, which has benefits such as increasing soil fertility, carbon storage, and prevention of dust storms. Management may include monitoring, reduction of trampling, and planting. Interventions can help maintain the integrity of biological soil crusts (biocrusts), which are ubiquitous microbial communities living in the top few millimetres of dryland soils. Biocrusts perform numerous functions, including adhesion of particles which protects the soil from erosion and is widely regarded as beneficial. Biocrusts also fix carbon and nitrogen from the air, enriching the soil and resulting in production of biomass. This living biomass is subject to natural selection pressures, and the soil-surface microbial community is expected to be adapted for life in this complex environment rather than being transient or opportunistic. In fact, biocrusts probably colonised the land long before plants, so we suggest that their survival and dispersal strategies are exquisitely adapted, and that they have had an ever-present influence on geomorphological processes for billions of years.

Whilst it is recognised that biocrusts stabilise soils and that certain cyanobacteria contribute significantly to this, there has been little work to practically verify identities and ecological strategies of stabilising organisms. Biological adaptations for dispersal by wind, water, or vegetative growth are expected, and such adaptations are considered likely to differently influence geomorphic processes and ecosystem function. Adhesive adaptations may contribute to landscape stability, whilst adaptations for wind dispersal may provide a mechanism for nutrient transportation and biogenic dust production.

To investigate biological dispersal and related geomorphic processes associated with biocrust organisms, we used DNA sequencing to characterise microbial communities of various biocrusts and sediments in Diamantina National Park of western Queensland, Australia ($23^{\circ}36'44.8"S$; $143^{\circ}17'46.9"E$). Climate in the region is semi-arid characterised by a summer-dominant rainfall pattern with a mean annual precipitation of 270 mm a^{-1} and high inter-annual variation. Central to the study site is 25 Km^2 of erosion active claypan, bordered by sand dunes and a river. Aeolian activity constantly moves sediment from the dunes and claypan, whilst periodic flooding (interval approx. 3 years) brings fresh river sediment and biological inoculum to the claypan.

We characterised the microbial community and physical properties of biocrusts situated in the claypan, on nebkha within the claypan, and on the sand dunes. River sediments were analysed in the same way, and a wind tunnel was operated on the sand dune to provide a controlled erosive treatment. Wind-eroded particles were analysed in comparison to adjacent untreated soil to determine whether particular organisms are preferentially mobilised or tend

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to stay adhered to the soil under windy conditions. These analyses yielded 18 million DNA sequences representing many thousands of distinct microbial taxa. The differential erosion of taxa from sand dunes, and their relative abundance at different sites will be discussed in relation to microbial ecology, geomorphology, and land management.



NOTES



Biological drivers and sediment behaviour in the Dee estuary, England.

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The earliest visible remnants of organismal life on Earth come from the fossil record of bacterial remains and laminated deposits preserved in early rock formations (cf 3.5 billion years BP). The laminated fossils, known as stromatolites, are clear early evidence of life but also of the impact of biology on sediment dynamics. Paleo-ecologists often debate what the form of ancient microbial remains, biofilms and mats tell us about the ambient conditions in the ancient environments when the material was first preserved. There is evidence that these early bacterial assemblages were capable of trapping and binding sediments, helping to create one of the first recognizable ecosystems on the planet. The stabilization of sediment at the interface between the bed and the water column allows biogeochemical gradients to become established, initiating the difference in local conditions (niche separation). This helps to promote specialization among bacteria that, in combination with ability "fix" those changes (improved fitness), drives the evolutionary process. The ability of organisms to affect their environment is well-known and often described as "ecosystem engineering". However, the examples of ecosystem engineers that are given are often larger charismatic species (elephants, beavers, otters etc.) while organisms such as bacteria, protists and algae, which are equally if not often more important, are less often described. There is a further interesting twist to the "ecosystem engineering" debate. Some evolutionary theorists consider that the alteration of the environment by organisms should in itself be recognized as an evolutionary pressure. The development of this theory, termed "niche construction" is somewhat controversial but seems a logical extension from the acceptance of the widespread nature of the "ecosystem engineering" process. However well-developed the theories of "ecosystem engineering" and "niche construction", the practical implications are of more concern to environmental engineers who are engaged with the fundamental question: *"To what extent must the impact of biological processes be taken into account when predicting the erosion, transport, deposition and consolidation cycle (ETDC) of natural sediments?"*

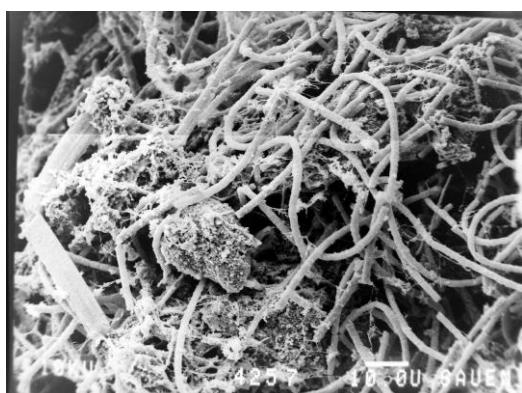


Figure 1: Binding of stromatolite material by cyanobacterial filaments and polymeric substances

This presentation will introduce some of the background to the investigation of stromatolite biodynamics (Figure 1) and consider the importance of this engineering activity in terms of the theory of niche construction and the importance of this paradigm in understanding sediment transport.

NOTES



Microbial mat sandwiches and other anactualistic sedimentary features of the Ediacara Member (Rawnsley Quartzite, South Australia): Implications for interpretation of the Ediacaran sedimentary record

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The Ediacara Member of the Rawnsley Quartzite of South Australia hosts some of the most ecologically and taxonomically diverse fossil assemblages of the eponymous Ediacara Biota—Earth's earliest fossil record of communities comprised of macroscopic, complex, multicellular organisms. At the National Heritage Site, Nilpena, fifteen years of systematic excavation and reassembly of bedding planes has resulted in reconstruction of over 400 square metres of Ediacaran seafloor, permitting detailed, *in situ* and continuous sedimentary, paleoecological and taphonomic assessment of Ediacara fossilized communities and the shallow marine settings in which these ecosystems lived. Sedimentological investigation reveals that the Ediacara Member consists of successions of sandstone event beds and a paucity of other lithologies. Moreover, these Ediacara sandstones are characterised by a suite of sedimentary features and style of stratigraphic packaging uncharacteristic of Phanerozoic sandstone successions deposited in analogous shallow marine, storm-dominated environments. These features, which are especially prominent in the Oscillation-Rippled Sandstone Facies (1–7) and the Planar-Laminated and Rip-Up Sandstone Facies and the Channelized Sandstone and Sand-Breccia Facies (8) of the Ediacara Member, include: 1) extremely thin (sub-mm- to mm-scale) and discrete bedforms, termed “shims;” 2) lateral discontinuity; 3) textural uniformity, including lack of disparity in grain size, between adjacent beds; 4) lack of amalgamation; 5) lack of erosional bed junctions; 6) doubly-rippled bedforms defined by rippled bed tops and bases which crisply cast the tops of underlying rippled beds; 7) ubiquity of diverse textured organic surfaces (TOS); and 8) texturally immature assemblages of sandstone rip-up clasts along bed tops. We interpret these features to reflect the presence of widespread matgrounds, which facilitated seafloor colonization by and ecological development of Ediacara macroorganisms in high-energy environments. Further, these observations suggest that pervasive matgrounds directly mediated both the formation and preservation of the anactualistic sedimentological features and stratigraphic packaging characteristic of the Ediacara Member. Additionally, absence of evidence for erosion or reworking in the Oscillation-Rippled Sandstone Facies suggests that these Ediacara stratigraphic packages capture a complete record of depositional events. Non-depositional ‘hiatuses’ are recorded by TOS and macrofossil assemblages and represent the duration of matground growth and matground-supported community development prior to the next depositional event. Ediacara stratigraphic ‘gaps’ are thus of unusually short duration, recording ecologically- rather than geologically-meaningful time scales, and variability within Ediacara stratigraphic packaging appears to more strongly reflect variability in ecological processes than in mechanical sedimentary processes. Moreover, the presence of Ediacara-style stratigraphic characters such as doubly-rippled bedforms, lack of erosional bed junctions and continuous stacks of sub-mm- to mm-scale

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sandstone shims of identical grain size that are nonetheless preserved as discrete bedforms provide criteria which, even in the absence of TOS (or MISS), can be used to infer the presence and influence of matgrounds upon the depositional and diagenetic history of sandstone-dominated stratigraphic packages.



NOTES



Hydraulic, gas exchange and biotic impacts on carbonation of high-pH waters

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The adjustment of the carbonate system to CO₂ gas exchange has long been considered a critical process within tufa and travertine depositional systems, and the role of biofilms is often assumed to primarily reflect consumption of CO₂ during photosynthesis. In most systems, the spring emerges with excess dissolved carbon and calcite precipitation is assumed to occur through Le Chatelier-like adjustment in the concentration of CO₃²⁻_(aq) during conversion of HCO₃⁻_(aq) to CO_{2(g)} at the air-water interface. This process is reflected by a rise in pH, and a loss of both Ca²⁺_(aq) and HCO₃⁻_(aq). Equilibrium is reached when a complex balance between falling Ca²⁺_(aq), falling HCO₃⁻_(aq) and rising pH bring the Ion Activity Product of Ca²⁺_(aq) * CO₃²⁻_(aq) to an equilibrium point unique to that system. At high pH, such as is found associated with the subsurface serpentine formation and also associated with sites affected by hyperalkaline pollutants (cementitious waste, pyrolysis ash, bauxite residue or steel slag), atmospheric CO_{2(g)} converts directly to CO₃²⁻_(aq). This newly formed carbonate will combine with calcium to form calcite until an equilibrium is reached by balancing falling Ca²⁺_(aq), falling HCO₃⁻_(aq) and lowering pH. This is entirely analogous to lower pH systems, except that carbonate ions are exclusively provided by air – water gas exchange, which should link mineral production more closely to this key process.

Here, we describe a series of experiments in which gas exchange, hydraulics, and biotic impacts were reductively investigated in a high pH system. Metal rich water with pH > 10 was produced by exposing water to highly reactive steel slag materials (mostly calcium silicate with minor calcium oxide), and these were pumped into a series of reservoirs where they could react with air pumped separately into the roofspace (Fig. 1). Mixing and gas exchange were enhanced in some reservoirs (cascades) and suppressed in others (ponds). Both types

of reservoir were tested after sterilization and after colonization by a biofilm recovered from a field site exhibiting similar water properties (Yarborough, North Lincolnshire, UK).

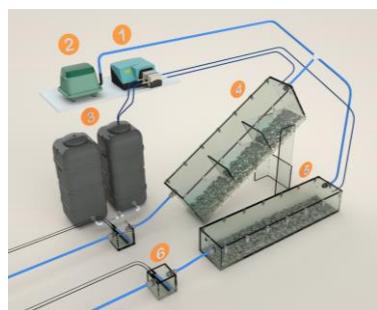


Figure 1: experiment design and physical configuration of reservoirs.

In the sterile case, calcium loss from solution in the cascades was enhanced by ~28% compared to the ponds (Fig. 2a), and despite significant variability in both the systems performed significantly differently ($p = 0.004$). Isolation of one system from air input demonstrates that this is limited by gas exchange, despite carbonate alkalinity in the influent water already being sufficient to drive mineral formation (45.03 ± 11.26 mg L⁻¹ CaCO₃).

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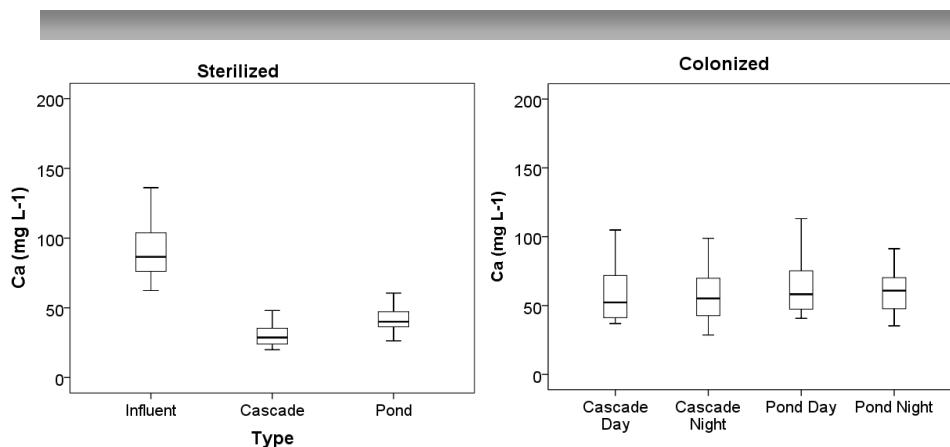


Figure 2: Calcium concentration on influent and effluent waters in sterilised systems (a, left) and colonised systems (b, right). Measurements were by ICP-OES at the University of Hull.

This effect disappears when the reservoirs are colonized by biofilms (Fig. 2b). Both ponds and cascades exhibit lower calcium loss from solution within the reservoir, higher variability, and no significant difference exist between cascades and ponds. Consequently, there is no evidence for gas exchange control on the equilibrium point of calcite formation once microbial systems are incorporated into the system. We conclude it would not be justified to use Le Chatelier-like dynamics to predict or explain calcite deposition unless a system could be demonstrated to be sterile in advance. Equally, we find no significant difference between effluents at night or during the day, indicating that CO₂ loss to photosynthesis is not altering the equilibrium position of these solutions. This is despite the saturation index of waters in ponds during the day being higher than in other systems (Fig. 3); although thermodynamically favoured, no additional calcite is actually forming. This also implies that the equilibrium position for the system is not controlled by the thermodynamic condition of the solution when biofilms are present within the system.

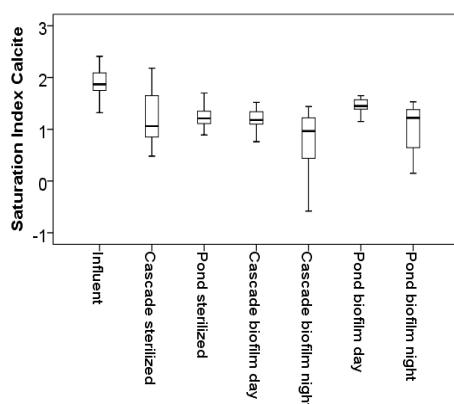


Figure 3: Calcite saturation indices for all experiments

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How far can biostabilisation go via EPS-mediated sediment erosion process?

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Understanding sediment dynamics has been a critical issue for hydraulic researchers and engineers for a long time. EPS-sediment systems are commonly observed on tidal flats while their working mechanisms on sediment erosion have not been fully understood. We designed process studies to isolate the temporal and micro-scale spatial variations in sediment stability caused by the established EPS matrix. Laboratory-controlled sediment beds were incubated with *Bacillus subtilis* for different periods before the erosion experiments. We found that the bio-bed showed different behaviours in erosion with different growth stages. At the first stage (5 days), the bed was more easily eroded than the clean sediment. With an increase of the growth period, bound EPS distribution evolved in vertical profiles resulting in bed stabilization. After 22 days, the bound EPS was highly concentrated on the surface as a biofilm, and extended to a depth of 0.5 cm with a relatively high content ($> 60 \mu\text{g/g.DW}$ polysaccharide), then decayed sharply at depth. The biofilm increased the critical shear stress, furthermore, it enabled the bed to withstand that threshold for an increased period because time was needed to detach the biofilm before eroding the sediment. After the loss of biofilm protection, the high content of EPS in the sub-layers continued to act as biostabiliser by coating and binding the sediment particles. Consequently, the bed strength did not immediately revert to the non-cohesive condition but progressively adjusted reflecting the depth profile of the EPS. Our results indicate that the EPS mediation in sediment stability may vary with the rhythms of microbial growth, and re-profile the sediment stability during different stages of cementing processes. A conceptual framework for sediment erosion is hence put forward to transform traditional sediment system to EPS-sediment system (Figure 1). It is highlighted that the dynamic variation regularities of bio-sediment await to be studied under the influences of multiple stressors in coastal environments (i.e., tidal and seasonal effects, waves, storms, etc.).

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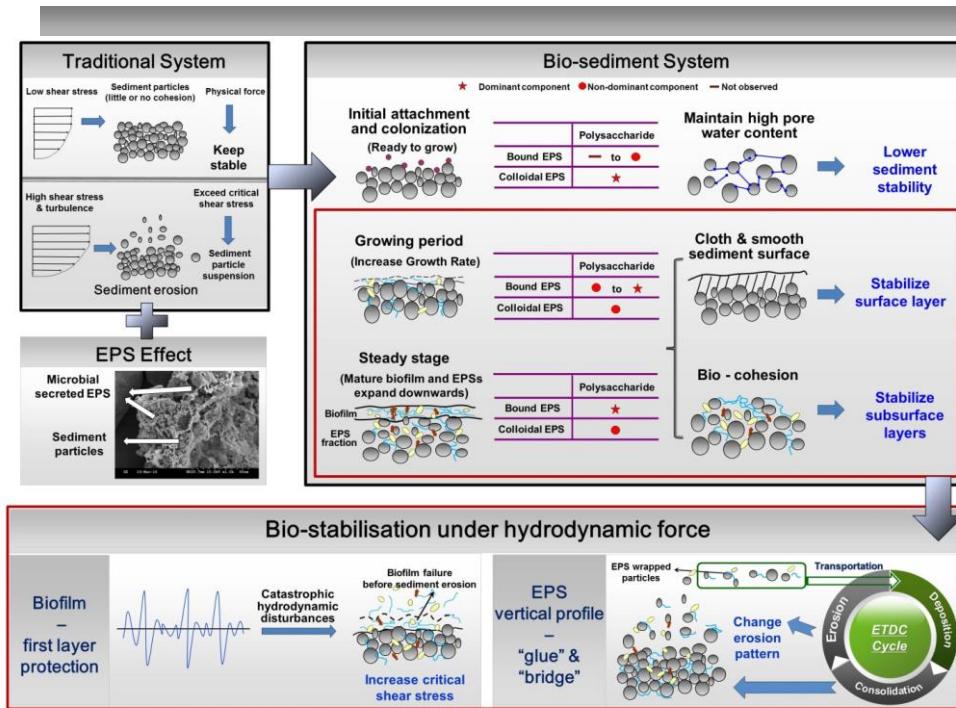


Figure 1. The conceptual model of how erosion processes can be mediated in bio-sediment systems compared to traditional systems. The performance of bio-stabilisation on mediating sediment erosion processes varies at different growth stages (of different consolidation ages) due to the different extents and vertical distribution of EPS. After erosion, EPS-wrapped particles can influence the whole of the ETDC cycle, changing the transportation and deposition processes by forming bio-flocs. Sediment consolidation with entrained EPS production sets up a new bio-sedimentary bed.

Acknowledgement:

The related contents have been submitted to a journal already. Presenting form of either oral or poster is accepted.

NOTES



Visualising the Role of Microbes in the Development of Sediment Flocs

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Microorganisms are ubiquitous to most aquatic environments, and their close association with cohesive sediment is well documented. In suspension, the interaction of microbes with sediment dramatically alters its behaviour, promoting flocculation and the downward flux of particulate matter to the bed. Developing sediment transport models that accurately account for these interactions depends on obtaining a more complete understanding of the processes and mechanisms governing bio-flocculation. Yet the fragility and multi-scaled nature of flocs makes their characterisation problematic.

Previous studies investigating flocs have employed correlative microscopy, a strategy involving the spatial registration of information collected at different scales using several imaging modalities. By combining conventional optical microscopy (COM) and transmission electron microscopy (TEM) it has been possible to visualise floc properties at the 'gross' (100s to 1000s μm) and nano-scale respectively. However, there remains a critical spatial gap between the resolutions of these two imaging techniques used that prevents a complete understanding of how structures at different scales are related. Additionally, since it is impossible to extract accurate 3D geometries from 2D projections, the information provided by COM and TEM is potentially misleading.

In this study, 'correlative tomography', a 3D expression of traditional 2D correlative microscopy, which exploits the recent developments in 3D imaging techniques, is employed to investigate sediment flocs for the first time. At the nanometre-scale, 2D scanning transmission electron microscopy (STEM) and energy dispersive spectroscopy (EDS) are employed to identify floc components. Accurate 3D data regarding the spatial arrangement and particle associations of floc components at the micro- and millimetre-scales are then obtained via focused ion beam nanotomography (FIB-nt) and X-ray computed tomography (X-ray CT) respectively. Subsequently, the multi-modal multi-scale datasets are 'fused' together in a 3D scene (Fig. 1) to better understand the relationships and interactions between organic (microbes) and inorganic floc components across the length-scales.

3D datasets obtained from natural estuarine floc samples demonstrate their compositional complexity and enable their hierarchical structure to be characterised. EPS is observed throughout the flocs coating the surfaces of primary particles (e.g., clays) and is inferred to promote the aggregation of microflocs. Larger floc structures (e.g., macroflocs) are facilitated by the presence of filamentous cyanobacteria, which due to their length and association with EPS act as anchors between multiple floc sub-structures (e.g., microflocs), forming a skeleton or 'backbone'.



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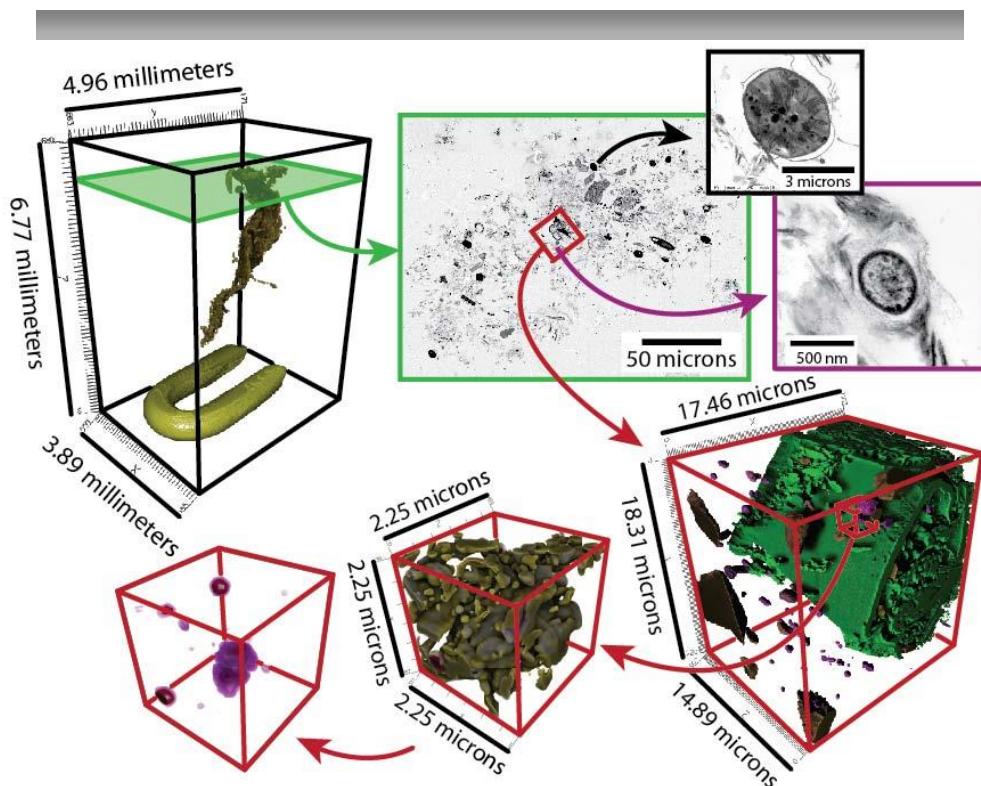


Fig. 1. The multi-scale structure of aqueous flocs: Top left image – macrofloc revealed using X-ray CT; Top middle image – STEM image of section through floc; Top right two images – cyanobacteria and microbial cell; Bottom three volumes – FIB-nt datasets showing decay organic detritus (green), clay minerals (brown) and microbes (purple).

NOTES



Poster Presentation Abstracts

Microbial communities inhabiting hypersaline microbial mats from the Abu Dhabi sabkha

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Microbial mats are organo-sedimentary structures that are typically found in areas with extreme environmental conditions. Since these ecosystems are considered to be representative of the oldest forms of life on Earth, the study of microbial mats can inform our understanding of the development of life early in the history of our planet. In this study, we used hypersaline microbial mats from the Abu Dhabi sabkha (coastal salt flats). Cores of microbial mats (ca. 90 mm depth) were collected within an intertidal region. The cores were sliced into layers 2-3 mm thick and genomic DNA was extracted from each layer. A fragment of the 16S rRNA encoding gene was amplified in all DNA extracts, using barcoded primers, and the amplicons sequenced with the Ion Torrent platform to investigate the composition of the microbial communities down the depth of the cores. Preliminary results revealed a high proportion of Archaea (15.5-40.8% abundance) in all layers, with *Halobacteria* appearing to be more significant in the first 40 mm (0.4-10.3% of the total microbial community). Members of the Deltaproteobacteria were dominant in almost all layers of the microbial mat ($\leq 48.6\%$ relative abundance); however this dominance was not reflected in the first 8 mm, where the abundance was less than 2%. Chloroflexi and Anaerolinea, representing $\sim 93\%$ of bacterial abundance, dominated the first 8 mm depth and decreased at greater depth ($\leq 3\%$ relative abundance). Cyanobacteria were found only in the top 10 mm, with unexpected low abundance ($\leq 3\%$ of the total number of reads). These results show a vertical zonation of microbial communities and processes in the microbial mats. Further analyses are underway to investigate if these patterns are repeated at other sites along a transect of the sabkha, and to relate the microbial composition to the physical-chemical conditions of the sites.



Textural variations in fluvial stromatolites: a record of biotic and abiotic processes

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Study of present-day carbonate deposition in fluvial systems allows correlation of the textural, structural, and isotopic variations of the deposits with the known environmental parameters. Monitoring of several rivers across the Iberian Range (NE Iberian Peninsula), involving artificial limestone substrates (tablets), has provided a 3- to 13-year sedimentary record that reflects seasonal variations in depositional rates that are mostly linked to temperature-dependent parameters. Stromatolites developed in fast-flowing (0.9 to 2.3 m/s) and shallow (< 7 cm deep) water have the highest accumulation rates and the most continuous record. In the River Piedra, from 1999 to 2012, mean growth rates of the stromatolites in fast-flowing areas was 9.5 mm/6 months during the warm periods (April to September) and 4.4 mm/6 months in the cool periods (October to March). In these areas, the water is oversaturated with respect to calcite ($SI_{calcite}$ from 0.6 to 1.0), with pH from 7.9 (cool periods) to 8.3 (warm periods), and mean monthly temperature between 21.7 and 25°C (July and August) and 2.4 and 7°C (December to February).

Stromatolites that form in the fast-flowing water of the River Piedra largely consist of dense, porous and, less common, macrocrystalline laminae (i.e. single units with homogeneous texture). The dense and porous laminae are formed of calcite tubes generated by calcite being precipitated around cyanobacterial filaments (mostly *Phormidium incrustatum*). In these tubes, most of the crystals are rhombohedral with crystal size increasing outwards (up to 15 µm long). The tubes, typically perpendicular to oblique to the substrate, locally produce fan-like geometries. Alternation of these dense and porous laminae (and in some cases a succession of the same type of lamina) produce dense composite laminae (3.5 to 15 mm thick; up to 8 laminae) and porous composite laminae (2 to 7.5 mm thick; 2 to 5 laminae). These composite laminae, which formed mainly in the warm periods and the cool periods, respectively, generally parallel seasonal temperature variations. The dense and porous laminae are linked to shorter (i.e., intraseasonal) variations in temperature, insolation, and hydrological conditions.

The macrocrystalline laminae consist of calcite crystals > 100 µm long that are perpendicular to substrate. These laminae, either alone or grouped into composite laminae up to 1.7 mm thick, are found at the base of tablet deposits (irrespective of the season of tablet installation), at the surfaces representing the time of tablet removal for measurements and on erosional surfaces. These facts suggest that macrocrystal precipitation occurred before microbial mats became first established or regenerated after their development was interrupted.

Textural attributes of partially synchronous laminated calcite deposits formed in a drainage pipe diverted from the River Piedra also support the notion that abiotic calcite precipitation favours formation of large calcite crystals, whereas calcite precipitation associated with cyanobacterial mats (i.e., influenced by calcite saturation at EPS) produces smaller calcite crystals that typically form around the microbes.

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What the physical rock record can and cannot reveal about a microbial role in the formation of ancient sedimentary signatures

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The global stratigraphic-sedimentary rock record is the repository of all of the remaining material evidence for historical Earth surface processes that operated during the last 3.9 billion years. Given recent advances in demonstrating the role of microbiota in forming sediments and influencing sedimentary processes, it is pertinent to try to understand whether there is any evidence of such activity in the physical rock record. Two aspects are considered in this poster: (1) direct evidence for microbial interaction with bedding planes (microbially-induced sedimentary structures (MISS)); and (2) the likelihood of large-scale bedforms in the rock record revealing evidence for microbial influence.

MISS – The rock record contains a rich variety of sedimentary surface textures on sandstone, siltstone and mudstone bedding planes. In recent years, an increasing number of these textures have been suggested to document the presence of surficial microbial mats at the time of deposition, resulting in their classification as MISS. The poster demonstrates claims for the stratigraphic restriction of MISS to intervals prior to the evolution of grazing organisms or after mass extinction events, as well as claims for the environmental restriction of MISS, are thus shown to result from sampling bias. We also suggest that raised awareness of MISS has come at the cost of a decreasing appreciation of 'abiotic' processes that may create morphologically similar features, and do not, fundamentally, require microbiota for their formation. We illustrate how elucidating the formative mechanisms of ancient sedimentary surface textures usually requires building up a suite of sedimentological evidence from surrounding strata, and that evidence for microbial presence must be robust in order to reject a null hypothesis of limited microbial influence on their formation.

Large-scale sedimentary bedforms – The rock record also contains an abundance of bedforms that do not necessarily require microbial life to form, but which can be seen to be modified under microbial influence in modern systems and experiments. Elucidating such influence in the rock record may only be possible in very limited circumstances. To avoid speculative conclusions, it is crucial to maintain the understanding that the rock record passively records sedimentary product, rather than ancient processes (which can only be determined from abstract interpretation beyond robust observation). The identification of a prokaryotic influence on the formation of specific bedforms preserved in the rock record is unlikely to be resolvable, due to the unlikelihood of both bedform and microbial fossil evidence being preserved, and adhering to the null hypothesis that the given bedform formed abiotically. Conversely, uncertainty regarding the evolutionary history of microbiota (e.g., the point at which EPS evolved), and evidence that microbial life existed since at least the Archean, means that it is presently impossible to confidently discern preserved bedforms that were demonstrably deposited in the *absence* of microbiota; as would be required a frame of reference from which to judge supposed microbially-influenced bedforms. Thus we advocate caution in interpreting geological sedimentary signatures, in order to avoid misleading claims regarding a microbial role, or not, in the formation of specific instances of preserved bedforms and sedimentary structures



Carbonate mineralisation in sabkha microbial mats; a comparative study of field and laboratory systems

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Microbial mats and their lithified counterparts are some of the earliest evidence of life on Earth. The coastal sabkha in Abu Dhabi, United Arab Emirates, is a modern setting where microbial mats flourish in a hypersaline and arid environment. These microbial communities are composed of microbes such as cyanobacteria, thermoplasma and sulphate-reducing bacteria. The mats thrive as they are protected from predators, which are excluded by the extreme environmental conditions. Microbial mats are highly reactive to change, with their microbial communities and geochemistry varying on a millimetre scale, likely controlling mineralisation processes.

Exact carbonate mineralisation rates within coastal sabkha microbial mats have not to date been quantified. Defining the mineralisation pathways and knowledge of precise mineralisation rates will help to explain how these organosedimentary structures are retained in the rock record. A fundamental understanding of the role of microbial mats in the formation of different carbonate phases is important, yet there are also other practical implications. For example, structures observed in core from the oil-bearing Arab Formation have been likened to modern microbial mats in terms of structure and mineralogy. The depositional configuration and primary mineralogy generated by microbial mats may control syndepositional lithification and later diagenesis thereby influencing reservoir porosity and permeability.

In order to constrain factors effecting mineralisation and early lithification, experimentation in a controlled laboratory environment is required. Parameters for experimentation have been established during fieldwork and were applied to a tank-based laboratory simulation of sabkha microbial mats. These parameters include light, salinity and cation and anion water chemistry, gas production chemistry and vertical mat growth. Parameters were measured weekly with sampling for mineralogical and microbial community analysis on a biweekly basis. In addition to these parameter measurements already in place in current experiments, temperature and tidal cycle were monitored in the field.

Over the course of the first three months, the microbial mat, which was submerged in an artificial seawater medium, grew vertically and developed a green surface at the top and sides. Thermogravimetric analysis has established that the top 1 mm surface mat biomass contains carbonate minerals, leading to an initial inferred carbonate mineralisation rate of approximately 0.5 g per 1 cm² per year (approx. per 10 g surface mat material). This rate of mineralisation will become more accurate as more analysis is completed particularly comparing samples of mat, initially before they went in to the tank experiment and after incremental time periods, 3 months, 6 months etc. Further analysis of mat growth will establish the extent to which the precipitated carbonate minerals result from microbial activity and the types of minerals precipitated. The rate of mineralisation can be scaled-up to the km scale with the potential to isolate mineralisation rates promoted by different communities and in different types of microbial mat.



Microbialite-coated rafts (giant "oncoids") from the Late Triassic lacustrine succession in the Jameson Land Basin, East Greenland

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Microbialite-coated rafts occur as a thin unit in the Late Triassic Edderfugleldal Member (a 55m thick mixed lacustrine carbonate and clastic succession) in the Jameson Land Basin, East Greenland.

The rafts as the central nuclei are made up of thin-layered siltstones and mudstones (shallow lake/playa facies), frequently intercalated with microbial carbonate sheets. They are commonly 3-10 cm thick, reach up to 1 m in length, and have sharp and angular ends. They are coated all around by microbialites, commonly 3-5 cm thick, giving rise to the rock a giant, flat-shaped "oncoidal" appearance (Fig. 1). On the upper side of the rafts, the microbialite crusts commonly have columnar forms that are frequently separated by brownish fine-grained infillings. On the underside of the rafts, the microbialite crusts in some places are less well developed, and display shrub- or thrombolite-like structures that have a peloidal-like texture in thin section view. The microbialites have very unsymmetrical crust thickness as the nuclei become to be small in size.

Some microbialite-coated rafts are folded and overturned. Under, and between, the larger rafts are smaller more chaotically organised microbialite-coated rafts, including portions of the microbialite coatings that have become detached. The smaller rafts form an intraclast breccia. In the most extensive example the microbialite-coated rafts overlie playa facies which show indications of erosion as well as soft sediment deformation. Along this basal contact an intraclast breccia is intermittently developed. Overlying the microbialite-coated rafts are intensively wave rippled shore-zone sandstones.

The rafts were generated under high energy conditions. Their sharp broken edges indicate that the raft material was partially lithified at the time of formation. However, the folding and buckling of the rafts, including their microbialite coatings, demonstrate that they also acted in a flexible manner. This may have been aided by the presence of microbial laminations which could have formed a cohesive and leathery carpet, rich in water and EPS. The complete microbialite coating suggests that the rafts were subject to regular re-mobilisation prior to their final deposition. However, the overturning of such large flat rafts would require significant energy. The common differences between the microbialite developments on the upper side and those on the underside suggest that the microbialite coatings could have formed *in-situ*. *In-situ* growth of oncoid coatings have been documented by a number of studies from lakes and rivers (Jones and Wilkinson, 1978; Leinfelder and Hartkopf-Froder, 1990; Hägele et al 2006). These studies suggested that the microbial coatings of oncoids do not necessarily require strong or repetitive turning. The microbialites (columnar form) formed on the upper side of the rafts may result from photosynthetic cyanobacterial activities. The peloidal microbialites usually formed on the underside of the rafts may be formed by microbes that could grow in dim light conditions.

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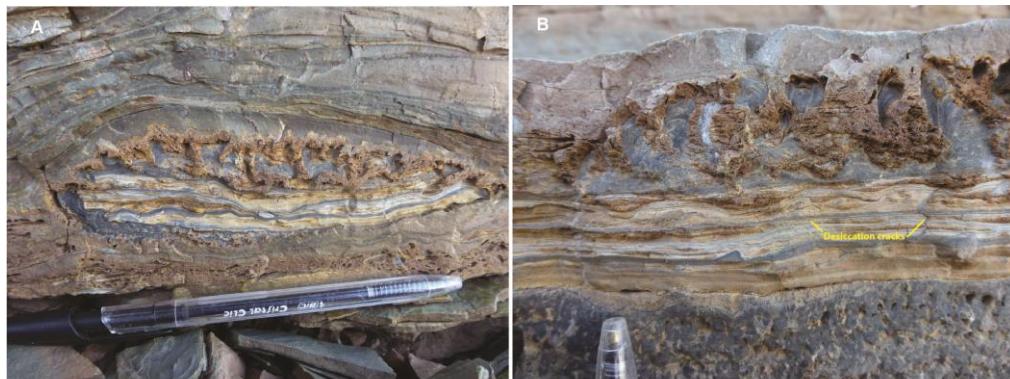


Fig. 1. Microbialite-coated raft. Edderfugledral Member, West Tait Bjerg, Jameson Land Basin, East Greenland. A: Long plate-like raft coated all around by microbialites. B: Close-up view of A showing the microbialite crusts that are columnar on the upper side and more bush-like on the lower side. Note the occurrence of desiccation cracks in the raft.

Microbialites after mass extinctions: change of life or anachronism?

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Carbonate microbialites appeared suddenly in shallow marine carbonate platforms directly after the end-Permian mass extinction and were widespread throughout Tethys Ocean, although poorly represented in other areas. Microbialites form very thin deposits, 6 cm to maximum ca. 20 m and appeared sharply after the extinction (commonly a discontinuity lies between latest pre-extinction limestones and the microbialite), and disappeared as sharply in the earliest Triassic. They recurred locally in the Early Triassic. The range of form of post-extinction microbialites is geographically distributed: 1) eastern Tethys, typified by the South China Block, is dominated by most closely resembling *Renalcis*-type microbes; 2) western Tethys microbialites rarely contain calcimicrobes, being dominated by sediment-constructed and cement-constructed stromatolites, together with thrombolites (which by definition are sediment-constructed).

No clear reason is currently available to explain differences between eastern and western Tethyan microbialite forms, but the widely distributed sudden appearance of microbialite forms after the extinction is considered by many authors to reflect earlier parts of Earth history, of Precambrian and Cambrian microbialites. Thus adoption of the concept of anachronistic facies, introduced by Sepkoski et al. in 1991, is common in literature, for apparently good reason. Precambrian cement stromatolites and thrombolites are common; and Cambrian calcimicrobes are major reef-building fossils, many include *Renalcis*-type calcimicrobes. Thus it is understandable that authors consider post-end-Permian shallow marine facies to have similarities to more ancient times. A further point is that the *Renalcis*-type calcimicrobe common in post-extinction South China is absent from the Late Permian reefs directly below, suggesting a return to environments of earlier times after the extinction.

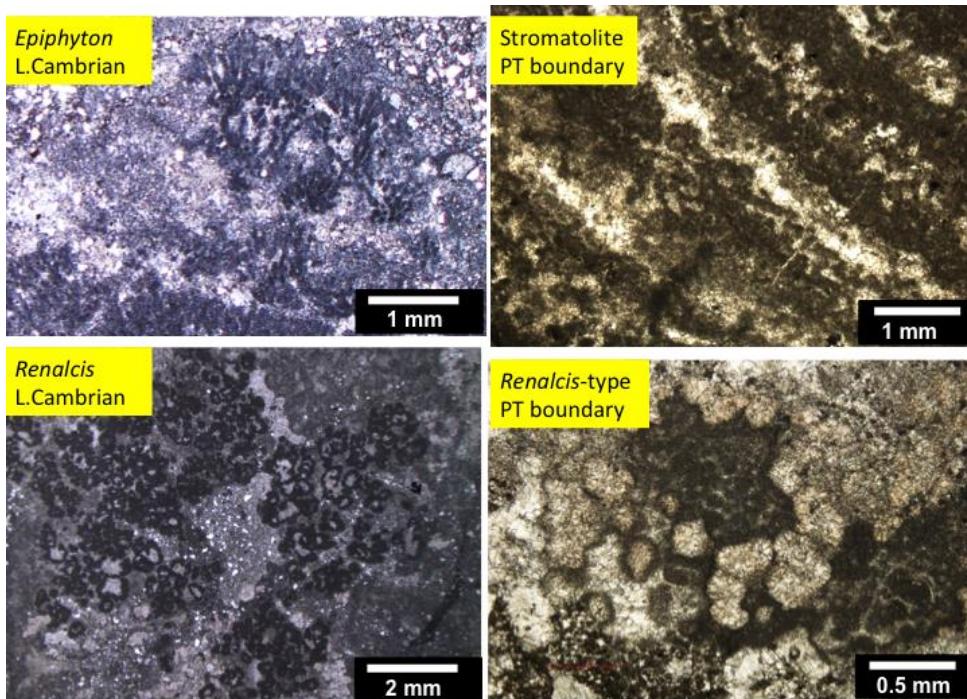
However, there is also good reason to consider application of anachronism concept to post-end-Permian facies to be obfuscating to analysis and understanding of events after the end-Permian because anachronism by definition refers to processes that are out of place in time. Microbialite and other facies that developed after the extinction did so because of catastrophic environmental change, which punctuated several hundred million years of more gradual Earth-surface environmental & tectonic change, and biotic evolution. Thus to consider post-extinction microbialites as anachronistic doesn't take account of differences between conditions existing during the Permian-Triassic boundary episode and earlier times, nor the intervening historical changes. For the end-Permian extinction, a dominating aspect is the Siberian volcanic eruption, the largest of the Phanerozoic, and major ocean changes that include widespread development of ocean anoxia. Another difference is that the calcimicrobe *Epiphyton*, globally a principal constructor of Cambrian reefs, is missing from post-extinction Permian-Triassic boundary facies. We cannot even be sure that renalcids in the end-Permian extinction facies is the same organism as those of the Cambrian.

Overall, we believe it is more useful and realistic to consider microbialites after mass extinction as relating to events taking place during that time, rather than viewing them as anachronistic. Thus, in relation to major points posed by the advertising text of this symposium, the Permian-Triassic post-extinction microbialites were opportunists taking



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advantage of favourable changes in Earth surface environments, and were thus bystanders reacting to events rather than driving them.



Biogenicity of fibrous microcrystalline calcite in vadose terrestrial settings

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Fibrous microcrystalline calcite (FMC) is a term that includes two basic habits of low Mg-calcite: *needle fibre calcite* (NFC), crystals with an average width of 1 µm and length reaching 10² to 10³ times their width, and *nanofibres*, curved fibrous crystalline forms of submicrometric dimensions. This type of calcite is one of the most ubiquitous forms of secondary calcium carbonate minerals in vadose terrestrial settings.

In calcareous soils and coarse-grained deposits (alluvial gravels, scree, etc.), FMC occurs in pores, mm to dm in size, forming patchy, cotton-like aggregates, typically accumulating within the rooting zone of terrestrial plants in semiarid/sub-humid climatic regions, typically characterized by seasonal moisture deficit. In caves, FMC is the main component of calcite moonmilk, a porous, soft, microcrystalline speleothem that can contain up to 95% of interstitial water, showing a distinctive pasty and plastic texture. Moonmilk can form extensive accumulations and occur in several morphological varieties of speleothems, from isolated patches and extensive 'flowstones' to stalagmites and stalactites.

The origin of FMC, particularly needle fibre calcite, has received broad scientific interest and has been attributed either to purely physicochemical processes or to microbial (generally fungal) biomineratisation. The current biogenic hypotheses have largely been based on: 1) positive association of soil FMC and calcite moonmilk with organic matrix and microbial communities (some of the microbes are culturable and able to precipitate carbonate in the lab); 2) presumptive geochemical and mineralogical/crystallographical evidence for calcite biomineratisation; and 3) similarity in dimensions and morphology of calcite fibres to fungal hyphae and filamentous bacteria. There is considerable evidence that deposits of FMC make specific microbial ecosystems in the vadose zone, what is particularly evident in soft, hydrated moonmilk, but the role of microorganisms and mechanisms of calcite precipitation remain uncertain.

An aspect, mostly ignored in the previous studies, is a possible passive role of organic matter in FMC precipitation. Growth of unusual, fibrous morphologies of calcite in the presence of organic polymers has recently been observed in materials chemistry experiments. Precipitation of calcite in these experiments can be compared to natural processes of organomineralisation (= microbially-influenced mineralisation) where the organic matrix, mostly microbial exopolymeric substances (EPS), influences crystal morphology and composition of distinctive forms of calcite - without living organisms and metabolic processes directly involved in mineralisation.

Our study is aimed at evaluating the mechanisms of biologically-induced vs. biologically-influenced vs. inorganic precipitation of FMC, mostly based on material from actively precipitating moonmilk deposits in four caves in Slovenia, and secondary soil carbonates forming within the rooting zone of plants in Mediterranean calcareous soils in SE Spain. Distinctive crystal shapes and growth patterns of FMC occurring in different underground ecosystems and geochemical settings strongly suggest a common mechanism of crystal growth, which is not necessarily related to fungi as in a generally accepted model of NFC precipitation. FMC crystal morphologies can be explained by concepts of nonclassical crystallisation systems where polymeric substances (EPS) probably provide a template for CaCO₃ nucleation and oriented growth.



Negligible microbial mat influence on ancient river functioning

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Following recent advances in the understanding of the influence of microbiota on extant sedimentary processes, it has been recognised that terrestrial microbiota (specifically microbial mats) likely played a role in influencing sedimentation in the geological past. The Precambrian and Cambrian non-marine realm was populated by mat-forming microbiota but devoid of higher plant life, and it has been proposed that such mats may have contributed to the stabilization of river landscapes in the absence of vegetation. The Precambrian and Cambrian alluvial rock record differs from its mid-Palaeozoic and younger equivalents in being dominated by accumulations of laterally-extensive, sheet-like sandstone strata with minimal mudrock; a fluvial style frequently referred to as “pre-vegetation”. Yet while the landscape-stabilizing effects of Palaeozoic embryophytes and other higher vegetation have been demonstrated, the specific influence of the non-marine microbial mats that formed the only continental biota before land plant evolution has been less well studied.

This poster considers two successions of sedimentary rock deposited by Precambrian-Cambrian river systems, in order to address the question as to whether microbial mats could have played a role in stabilizing river channels in the absence of land plants; 1) The Ediacaran-Cambrian Series Rouge of northern France and the Channel Islands; 2) The Mesoproterozoic Meall Dearg Formation of NW Scotland. Both are examples of pre-vegetation alluvium containing the rare conjunction of both (a) fossil evidence for the existence of terrestrial microbial mats in the depositional environment, and (b) sufficient exposure of alluvial architecture to permit a refined interpretation of fluvial sedimentary style. Evidence for microbial mats includes probable mat fragments and mat-related microtextures preserved in argillaceous sediment and revealed in thin section, as well as a suite of distinct sedimentary surface textures on outcrop bedding planes; including named forms such as *Aristophycus*, *Manchuriophycus* and *Arumberia* (traditionally classified as ‘pseudofossils’ but now more readily explained as fossilised mat features). Selected sedimentological characteristics of the Series Rouge and Meall Dearg Formation are described and analysed. In both case studies, preserved sedimentary architecture contains sedimentary motifs that are typical of other examples of pre-vegetation systems, with or without microbial mat evidence. We argue that the surficial cohesion provided by matgrounds was ultimately insufficient to offer long-term resistance against reworking by hydrodynamic processes, on the time scale of active deposition; thus the preserved sedimentary architecture is biased to reflect abiotic processes of eventual fluvial reworking of channel margins. As such, these formations contain positive evidence indicating that microbial mats alone were unable to stabilize river banks during the Precambrian-Cambrian; a contention that finds support from modern observations of bank-undercutting of biological soil crusts.



**Microbial processes in Neoproterozoic sediment diagenesis:
Evidence in the Aberfeldy stratiform baryte deposits, Grampian
Highlands, Scotland**

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The Aberfeldy baryte deposits are the largest UK resource of this industrial mineral: >1 million tonnes have been extracted at Foss Mine since the 1980s. The bedded mineralization and enclosing metasediments comprising the Ben Eagach Schist Formation were deposited in the Neoproterozoic at around 630 Ma, and were regionally metamorphosed and tectonically deformed in the mid-Ordovician Grampian Orogeny (Moles 1985; Treagus *et al.* 2013). Marble-textured baryte rock forms beds up to several metres thick. The mineralized beds additionally contain barium silicates (celsian, hyalophane), carbonates (calcite, dolomite) and sulphides (pyrite, sphalerite, galena). They are interpreted as chemical sediments precipitated from hydrothermal fluids that were episodically exhaled into a marine basin filling with organic-rich mudstones, siltstones and sandstones (Moles *et al.* 2015). Here we present evidence for microbial processes that influenced the mineralogy and isotopic geochemistry of the stratiform mineralization and adjacent sediments.

Small modal proportions of the barium carbonates witherite BaCO_3 , barytocalcite $\text{BaCa}(\text{CO}_3)_2$ and norsethite $\text{BaMg}(\text{CO}_3)_2$ are associated with baryte and carbonate rocks. Initially located by their distinctive cathodoluminescence (Fig. 1a), the barium carbonates occur as inclusions typically 10s of micron across within millimetre-sized crystals of pyrite and other non-carbonate minerals. Crystallization of barium carbonates is ascribed to low sulphate activities in the pore waters of the chemical sediments during early diagenetic processes associated with biogenic sulphate reduction (Fig. 2). Textural evidence suggests that barium carbonates were common before regional metamorphism, and were mostly replaced in the rock matrix by non-barium carbonates + secondary baryte produced during sulphidation reactions. Comparatively low $\delta^{34}\text{S}$ values (16–22‰) of this secondary baryte indicate sulphur derived from reduced sulphide.

$\delta^{34}\text{S}_{\text{baryte}}$ ratios in primary baryte rock are typically $36 \pm 1\text{\textperthousand}$. This is interpreted as the isotopic composition of contemporaneous seawater sulphate (Moles *et al.* 2015). $\delta^{34}\text{S}_{\text{sulphide}}$ ratios of 12–18‰ in the host metasediments is consistent with microbial reduction of seawater/porewater sulphate. Atypically low (32–35‰) and high (37–40‰) $\delta^{34}\text{S}_{\text{baryte}}$ ratios occur within ~0.5m of baryte bed margins, showing considerable variation over short distances. Baryte $\delta^{18}\text{O}$ ratios scatter about a mean of $13.5 \pm 5\text{\textperthousand}$ and show bed-marginal variation similar to $\delta^{34}\text{S}_{\text{baryte}}$. In some cases the trends are very similar and the ratios increase and decrease in parallel, while elsewhere they show opposing trends (Fig. 3).

These isotopic variations are attributed to post-depositional alteration while the baryte sediment was fine-grained and porous. Likely mechanisms include infiltration of ^{32}S - or ^{34}S -enriched fluids into the marginal baryte, or ^{32}S depletion during partial dissolution of baryte which is known to be enhanced by increases in temperature and salinity and by strain-induced recrystallization. Fluid-mediated transfer of dissolved barium and sulphate into the adjacent metasediments likely contributed to the observed barium enrichment and formation of millimetric crystals of baryte that cut across sedimentary lamination (Fig. 1 b,c). The most likely timing for this was during diagenesis and fermentation of organic matter in the



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enclosing sediments. In such sediments, pyrite formation can generate differential isotope concentration gradients for ^{32}S - and ^{34}S -containing solutes (Torres *et al.* 1996), leading to enhanced downward diffusion of ^{32}S -enriched sulphate and upward diffusion of ^{34}S -enriched dissolved sulphide.

Despite metamorphism, the baryte beds thus preserve key evidence for microbial activity within organic sediments in the Neoproterozoic.

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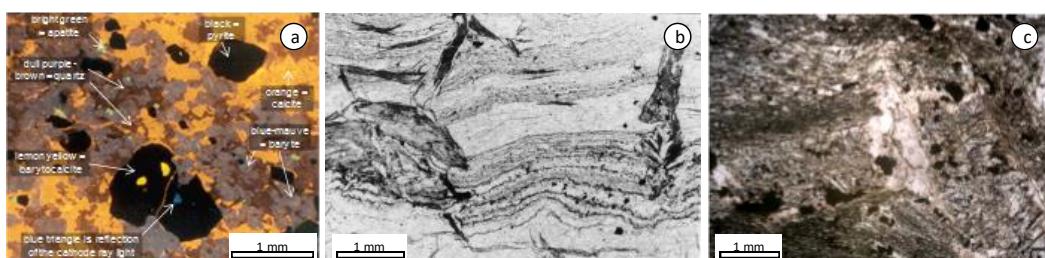


Figure 1: Textural and mineralogical features of baryte-carbonate-sulphide rock and mineralized sediment in thin sections: (a) quartz-pyrite-baryte-calcite rock in which pyrite contains inclusions of barytocalcite (cathodoluminescence); (b) silicified sediment preserving fine sedimentary laminae of graphite and pyrite showing displacement by diagenetic crystals of gypsum, subsequently pseudomorphed by carbonate and hyalophane (transmitted light); (c) mineralized sediment containing tabular pseudomorphs after diagenetic baryte crystals that displaced the sedimentary laminae (TL).

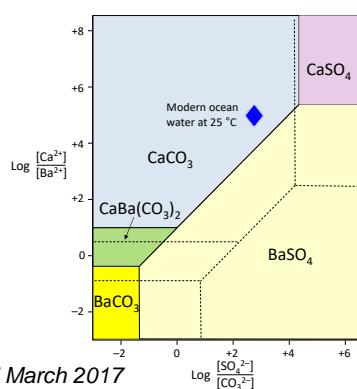
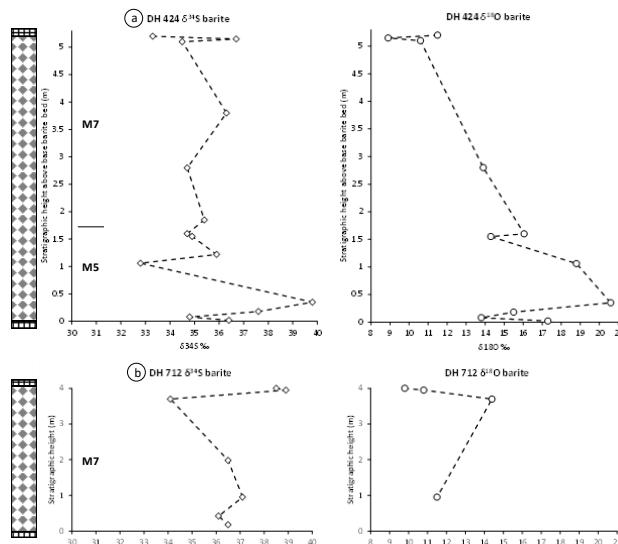


Figure 2: Activity diagram of part of the system $\text{CaO}-\text{BaO}-\text{H}_2\text{O}-\text{CO}_2-\text{H}_2\text{SO}_4$ at 1 atmospheric pressure. Solid lines show boundaries at 25°C ; dashed lines show boundaries at 200°C . A field for barytocalcite

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$\text{BaCa}(\text{CO}_3)_2$ is inserted, although its upper boundary is speculative. Sulphate activities much lower than seawater are required to permit formation of barium carbonates.



the baryte rock from adjoining metasediments.

Figure 3: $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ profiles for pure baryte separates (Moles *et al.* 2015) from Dresser Minerals boreholes (a) DH424 in Foss West showing two stacked baryte beds; (b) DH712 in Foss East, upper bed only. Thin chert beds top and bottom separate

Gordia Emmons (1844) – a composite trace fossil from the Hirnantian of the Welsh Basin

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The end-Ordovician extinction event is generally regarded as being the second most significant extinction of the “Big 5” Phanerozoic Extinction episodes. Associated with the Hirnantian *anceps* and *extraordinarius* graptolite biozones the extinction is intimately associated with the “ice house” world caused by the Hirnantian Glaciation. Hirnantian strata outcrop, and are seen in spectacular coastal exposure, around the coastal village of Llangrannog, Ceredigion, West Wales.

Despite the seemingly complete absence of fossils in the rocks there is evidence (in the form of trace fossils and Microbially Influenced Sedimentary Structures) that Hirnantian oceans were far from being sterile. This paper describes a distinctive occurrence of the ichnogenus *Gordia* Emmons (1844).

Published descriptions of *Gordia* relate only to the “horizontal scribbles” of the meandering grazing burrow system. In this example these are typically 1mm diameter, and appear not to follow any systematic grazing strategy. The burrow system (Fodinichnia) trace links to an epibenthic “portal” and a series of vertical shafts, presumably important for ventilating the burrow network. The “access burrow” (Repichnia) is of a slightly larger diameter than the grazing trails, and displays a convex upwards base (this may be a post mortem response of the substrate to “heave” of the burrow floor).

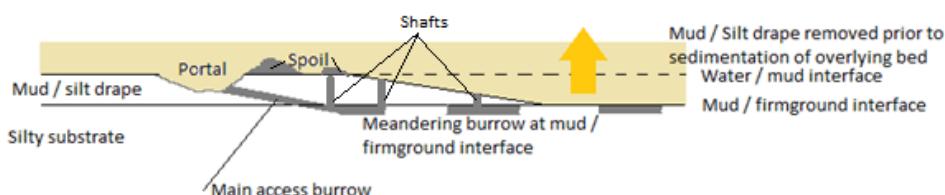


Figure 1: Illustration of the architecture of the *Gordia* trace fossil

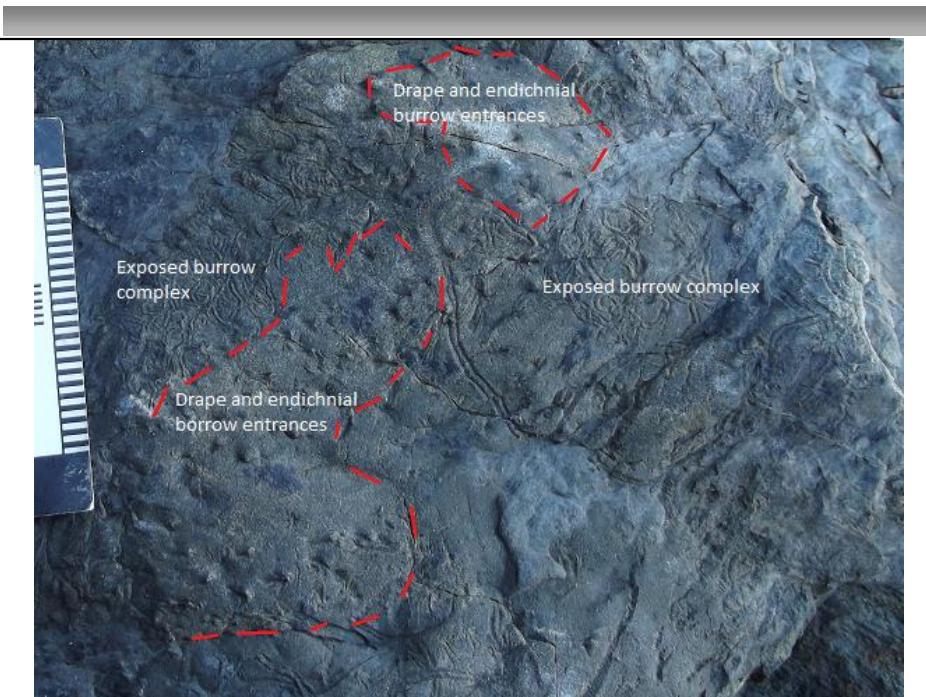


Figure 2: *Gordia* undermat mining complex with burrow complex of small “scribbling” traces, access drive and silt drape surface (red) with portal pit and cast features

Microbially Influenced Sedimentary Structures associated with the Hirnantian extinction episode in the Welsh Basin

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Ynys Lochtyn is a small peninsula on the west coast of Wales where latest Ordovician (Hirnantian) rocks are exposed. The rocks immediately underlie the Mottled Mudstone Member (*persculptus* biozone) and the mapped basal Silurian strata. Despite the absence of macrofossils the strata can be assigned to the *extraordinarius* biozone, and are therefore coeval with the end Ordovician glaciation and extinction episode.

The rocks display a wide range of trace fossils including *Gordia* (see Poster Presentation, aff. *Merastomichnites*, aff. *Thallassinoides* and *Nereites*), as well as a number of unusual bedding surface structures (aff. *Kinneyia*) which are believed to represent biofilms. The rocks appear to be of a shallow marine origin, with rippled bedding surfaces commonplace.

Further east in the Welsh Basin, in the eponymous Cwm Hirnant, macrofauna are present in the form of a typical *Hirnantia* Fauna present in the oolithic Hirnant Limestone Member and Hirnant Mudstone Formation, including both *Hirnantia sagittifera* and *Eostropheodonta Hirnantensis*. Trace fossils are absent, however isolated occurrences of what appear to be biofilms are present, although they show destruction related features, suggestive of desiccation. This is consistent with observations of possible karstic weathering features in the Hirnant Limestone as a result of sub-aerial exposure, associated with glacio-eustatic drawdown.

It is postulated that the presence of microbially activity is a direct result of the extinction amongst the macrofauna, and reflects an apparent reversal of the generalised deepening of the Taphonomically Active Zone (Wright and Cherns, 2016). The trace fossils present are all either shallow burrow systems, or epibenthic features, reflecting a reordering of the palaeoecology.



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Figure 1: *Kinneyia* type ripples, Ynys Llochlyn



Figure 2: Upturned margins of dessicated? biofilm, Cwm Hirnant

Evolving use of ecospace in early Phanerozoic deep-marine environments revealed by biosedimentary structures and ichnofabrics

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The concepts of the Agronomic Revolution and Cambrian Substrate Revolution refer to the changes in the ecological structure of infaunal marine communities during the late Neoproterozoic to early Phanerozoic interval. In summary, these changes involve the shift from 'matgrounds', (substrates bound at their surface by microbial mats) to 'mixgrounds', characterised by high substrate mobility due to the activities of vertically bioturbating macrofauna. The effects of this transition on the chemical, biological and physical properties of sediments would have been profound, but are as yet poorly understood. Further, the timing of the transition and its duration are poorly constrained; there is no *a priori* reason to assume it occurred rapidly, or was synchronous globally.

Biosedimentary structures, including microbially induced sedimentary structures (MISS), discrete trace fossils and ichnofabrics are a critical, probably the principal, source of data available to reconstruct the geological history of this major transition in the evolutionary history of the biosphere.

Biosedimentary structures preserved within turbiditic strata on the NW facing margin of Eastern Avalonia during the middle-late Cambrian (Booley Bay Formation and Bray Group, SE Ireland) provide important data on the ecology of infaunal communities at this time, but also insight into the physical properties of the sediments.

(1) Thin intervals (<10mm thick) of vertically anastomosing clay-organic laminae are interpreted as the remnants of surficial microbial mats. These are associated with thin intervals (a few mm thick) in which the bedding parallel fodinichnion *Oldhamia* occurs in remarkably high densities, providing direct evidence of its producer being an undermat miner.

(2) Detailed logging shows that sedimentary textures remarkably similar to MISS occur inside event beds (typically in the Tc interval), not at the interface between beds, on what would have been the sediment-water interface.

(3) Other intervals are characterised by the occurrence of remarkably high densities of horizontally oriented sand-filled burrow networks on the base of event beds and in the upper, muddy, part of the underlying bed. These were open burrow structures that formed a very short distance below the sediment water interface, and to which they were connected by short vertical extensions. These open structures were preserved by passive infill of sand sourced from the next event bed as it deposited. The infill of the open structure inside the underlying bed, not just as casts on the sole of the depositing bed, plus the close spacing of the open burrow networks requires the sediment to have been remarkably cohesive (stiffened). There is, however, no evidence for either syn sedimentary cements nor the sediments having been microbially bound.

These data add to growing evidence that the transition from matgrounds to mixgrounds in early Phanerozoic deep-marine environments of eastern Avalonia was protracted, and characterised by an intermediate stage in which matgrounds persisted in certain environmental settings, but in others sediments were firmgrounds. Structures remarkably similar to the textures of MISS can be produced purely by physical processes at the time of deposition of events.



Lithification of laminated microbial mats in the coastal sabkha of Abu Dhabi (UAE)

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Lithified remains of microbial mats are documented from a range of ancient and Recent marine and terrestrial environments. These features are often referred to as stromatolites, based on their relic laminations which stem from precursor laminated microbial mats. Lithification of these stromatolites is the result of the trapping and binding of allochthonous grains and the microbially mediated and/or controlled precipitation of mineral phases. While the Abu Dhabi coastal sabkha is well-known for its extensive laminated but non-lithifying microbial mat belt, no true stromatolites have been reported from this area so far. Here we report the first evidence for lithifying laminated microbial mat, or stromatolites, from an intertidal locality in the coastal sabkha of Abu Dhabi. We characterise the conditions in which these stromatolites form and describe associated lithification processes, based on environmental and sedimentological analyses.

Our observations were made in a hypersaline intertidal pool, which lies within the laminated microbial mat zone. The pool is characterised by near-vertical, partially undercut, but lithified stromatolitic margins that rise between 20 to 30 centimetres from a basal hardground. Individual stromatolite build-ups are observed in the centre of the pool. An organic, partially-anoxic ooze floors the areas between the pool margins and the stromatolites. Stromatolites and the pool margins are partially overgrown with *Chrysophyta*, fish are episodically observed in the pool. Salinity in the pool ranges between 75 - 100 permil, temperatures vary seasonally between 12 - 46°C, and water depths range between 5 - 75 cm. Circulation of the pool water is controlled by the mixed semi-diurnal tidal cycle and by adiabatic winds.

The conceptual model we propose incorporates that the intertidal pool is the result of erosion and subsequent lithification of an area of precursor laminated microbial mat. These lithification processes may have been initiated by a change in the associated microbial communities from non-lithifying to lithifying taxa as well as changes to the pore-water chemistry, that resulted from prolonged exposure to sea water. Further extension of the pool area occurred through undercutting and subsequent breakoff of the lithified margin. After breakoff, parts of this lithified margin were left behind and form isolated stromatolites. Ultimately, we are documenting the switchover from a non-lithifying to a lithifying microbial system, initiated by a random erosive event in the past.



Microbial Biofilms drive Global Carbonate Production Rates

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Carbonate precipitating microbial biofilms are ubiquitous in present day shallow freshwater to hypersaline environments. Skeletal stromatolites, precipitating calcite into laminar sheets, are the first colonial fossils preserved followed by thrombolites (Late Proterozoic to Recent). Current research at Hull has focussed on mesocosm propagated freshwater microbial thrombolite cultures and has demonstrated their ubiquitous global distribution and close relationships and structure to shallow marine counterparts. This work also demonstrates a mechanism for calcium carbonate precipitation within the microbial biofilm EPS and has revealed the importance of microbial biofilms in global lime mud production.

Much Late Proterozoic to Recent detrital micrite (lime mudstone) originates from microbial biomediation processes and subsequent biofilm disintegration. Significantly, the vast volume of this material in the Phanerozoic record testifies to the role of subaqueous microbial biomediation in balancing the global carbon budget.

The precipitation process in thrombolites involves collaboration between phototrophic and heterotrophic microbes (including cyanobacteria and diatoms) within the communal EPS biofilm. These are organised into guilds which collaborate in the stabilisation of calcium ions which would otherwise inhibit colony metabolism. These precipitates are engineered into a structural framework at specific sites within the EPS. The resulting 3D vacuolar fabric provides rigidity to the accreting colony and permits rapid build-up and colony progradation. This optimises colony position and elevation above shifting substrates in order to maintain access to nutrients and light. Calcite-precipitating thrombolite fabrics provide maximum colony strength for minimum precipitate volume (cf. skeletal stromatolites which are constructed of basal laminae only).

The downside is that the exposed thrombolite surface is easily damaged by grazers and turbulence. Large volumes of EPS and particulate carbonate are constantly lost to the surrounding shelf and depocentres. It is this fine detrital carbonate mud which is a major contributor to Late Proterozoic carbonates.

SUMMARY

1. The biofilm community encourages precipitation of chelated ions (normally Ca^{++}) into amorphous low-Mg CaCO_3 nanospheres (*Probably because these unwanted cations interfere with other ionic transfer processes during biofilm metabolism*).
2. The resulting internal calcite framework provides a scaffold enabling the colony to outstrip background sedimentation and shoulder-off competition. (*These are the first organised life-forms with the ability to dominate their environment*).
3. The price for this rapid response is that the colony surface is easily damaged. (*storms and grazing cause a constant shedding of mud-grade carbonates and EPS fragments*).
4. Although freshwater, marine and hypersaline environments each support their own specific thrombolite biofilm guilds all function similarly in respect to carbonate precipitation and lime-mud production.

MICROBIAL BIOFILMS ARE PROBABLY THE MOST IMPORTANT CARBONATE PRODUCERS ON THE EARTH'S SURFACE



Recognizing microbial mats in fluvial-tidal siliciclastic deposits affected by very low-grade metamorphism: comparison of the dinosaur track-bearing Oncala Gr (Lower Cretaceous, N Spain) with present-day examples from Argentina

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Present-day tidal flats are commonly colonized by microbial mats, which alter sediment properties as a consequence of the interaction between microorganisms and sediments. Thus, their recognition in ancient siliciclastic tidal deposits is important to understand their impact on sediment dynamics and their role on the formation and preservation of sedimentary structures, such as vertebrate footprints.

This is the case of the Oncala Gr, which was deposited during the Berriasian in the Cameros Basin, located in northern Spain. The Oncala Gr contains siliciclastic deposits made up of laterally continuous layers of interlaminated mudstone, siltstone and very fine to medium-grained sandstone, and meander loop bodies showing inclined heterolithic stratification, which are interpreted as formed in broad fluvial-tidal flats traversed by meandering channels. These deposits are characterized by ubiquitous tracks of dinosaurs and other vertebrates, and desiccation cracks. The Oncala Gr was buried under more than 5000 m of Cretaceous sediments, and was affected by very low-grade metamorphism.

Despite the important compaction and metamorphism of the Oncala Gr, the comparison of the laterally continuous, laminated siliciclastic deposits of this unit with present-day microbial mats from the upper intertidal-supratidal flats of the Bahía Blanca Estuary and from a supratidal plain in Paso Seco (Argentina) allowed the identification of the following characteristics and microbially-induced sedimentary structures (MISS): 1) Extremely thin (100 µm-1 mm) lamination made up of alternating siliciclastic mudstone and siltstone/fine-grained sandstone, occasionally showing pinch and swell structures, which resembles present-day biolaminites (Figs. 1A-D). 2) Mudstone laminae show 0,3-1 mm tall pinnacle microstructures (Fig. 1C), strikingly similar to the erected bundles of cyanobacteria filaments developed in areas of the supratidal plain of Paso Seco that remain flooded for long periods of time. 3) Sand grains floating within the mudstone laminae, resembling the grains included within the biomass layers of the biolaminites of the upper intertidal-supratidal flats of the Bahía Blanca Estuary (Figs. 1E-F). 4) Rippled sandstone layers showing thin mud laminae draping the foreset laminae, like the ones in the upper intertidal-supratidal flats of the Bahía Blanca Estuary resulting from repetitive rapid colonization and production of biomass on the ripple lee faces, followed by a new sand input covering the leeward slopes. 5) Rectangular mud chips, similar to fragments of present-day desiccated microbial mats reworked by storms in the upper-intertidal flats of the Bahía Blanca Estuary or wind currents in the supratidal plain of Paso Seco. 6) Lamina top surfaces speckled with rounded particles, which could be similar to the dispersed grains stuck on the surface of the present-day mats. In addition to these, typical MISS from ancient sediments, such as wrinkle structures (Fig. 1G) and irregular polygonal textures (Fig. 1H) on lamina top surfaces, are also present. All these evidence indicate that the siliciclastic flats of the Oncala Gr were likely colonized by microbial mats. Thereby, the biostabilization of the sediments allowed the preservation of



delicate sedimentary structures (such as thin lamination, desiccation cracks at the top of every submillimetre-thick mudstone lamina, consecutive ripple trains, and tracks) in an environment affected by tide and wave currents that would have otherwise eroded them. Moreover, microbial mats probably prevented the formation of deep dinosaur tracks in the predominantly fine-grained sediments of the Oncala Gr, as occurs nowadays when stepping on modern, cohesive microbial mats (Fig. 1I-J).

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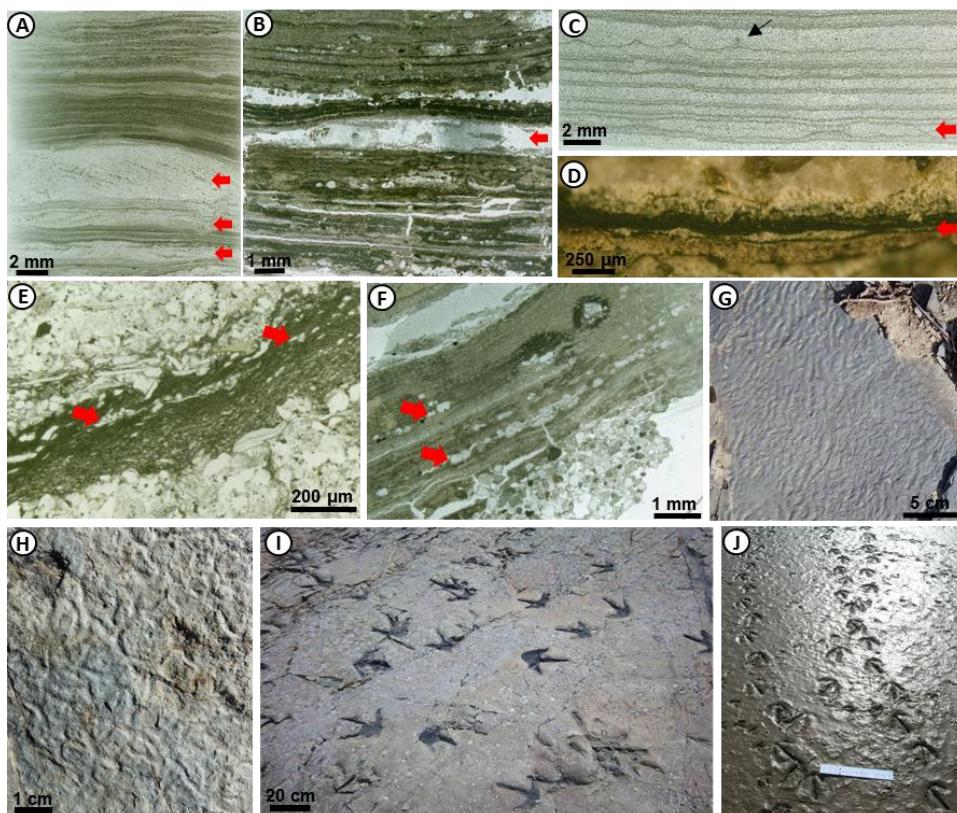


Fig. 1. **A)** Oncala Gr: Thin-section micrograph of alternating mudstone and siltstone/sandstone thin laminae, interbedded with thicker, rippled sandstone laminae (arrows). **B)** Bahía Blanca Estuary: Thin-section micrograph of biolaminites, interbedded with a thicker sand lamina (arrow). **C)** Oncala Gr: Thin-section micrograph of alternating sandstone and mudstone laminae. Note the pinnacles in a mudstone lamina (black arrow) and the pinch and swell structures in a sandstone lamina (red arrow). **D)** Paso Seco plain: Cross-section of pinch and swell structures in a sand lamina within a microbial mat. **E)** Oncala Gr: Thin-section micrograph of sand grains floating within a mudstone lamina. **F)** Bahía Blanca Estuary: Thin-section micrograph of sand grains within a biomass layer. **G)** Oncala Gr: Wrinkle structures on top of a mudstone lamina. **H)** Oncala Gr: Irregular polygonal textures on top of a mudstone lamina. **I)** Oncala Gr: Shallow dinosaur tracks on top of a sandstone layer covered by a thin mudstone lamina. **J)** Paso Seco plain: Rhea tracks on microbial mats.

Influence of sterile Extracellular Polymeric Substances on calcite growth and trace element incorporation

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Microbial biofilms are believed to influence calcite morphology, precipitation rate and trace element ratios, but the roles of metabolic processes and the presence of extracellular polymeric substances (EPS) are difficult to disentangle. EPS substances have been shown to chelate cations such as calcium and magnesium from solution in a chemoselective manner, thus influencing both the saturation state and trace element composition of the bulk water and any precipitates. The presence of other positive ions such as Na⁺ may impact on the chelation dynamics of cations such as Ca²⁺ and Mg²⁺ with a consequential impact on the trace element ratios of precipitated calcite. Equally, bond formation and breaking is a thermally regulated process meaning that EPS-water-solid behaviors may vary significantly over small environmental gradients. Here, we describe a series of experiments in which precipitation rate and trace element (Mg) incorporation into precipitated calcite are investigated over the temperature range of 12 to 18 °C and salinity range 0 to 40 mg L⁻¹ NaCl_(aq). This is done under sterile conditions in the presence of variable EPS concentrations. The EPS was directly extracted from naturally occurring tufa biofilm (River Lathkill, UK).

In the presence of EPS, precipitation rate decreases with temperature. An exponential increase in (Mg/Ca)_{calcite} occurs as a function of temperature with an exponential constant of 0.31, regardless of EPS additive presence. This is close to those found in calibration equations for foraminiferal calcite. However, this relationship was not previously found in the precipitates grown within living biofilms. Clearly, the growth rate control found associated with living biofilms is a result of microbial metabolic processes, and not simply the presence of EPS molecules.

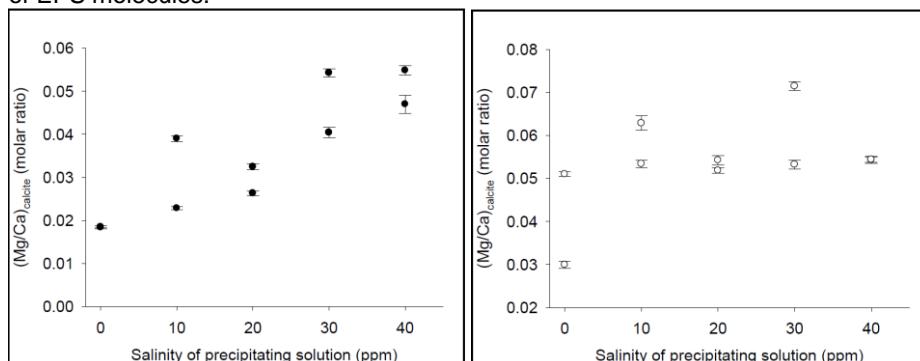


Figure 1: Mg/Ca in calcite precipitated under sterile conditions a) left, in the presence of EPS and b) right, in the absence of EPS.

Salinity increase correlates to precipitation rate decrease both in the presence and absence of EPS, but the relationship has a higher gradient where EPS is present. In contrast to previous studies which have shown that EPS decreases precipitation rate, we find the tufa EPS actually increases calcite production at low salinity (Fig. 2). Due to the steeper gradient with salinity in the presence of organic additives, this impact decreases as salinity increases so that above seawater salinities a negative impact from EPS may be found, as described in the literature. (Mg/Ca)_{calcite} increases by about 3 % per 1 mg L⁻¹ increase in salinity in the



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presence of EPS (Fig. 1a). As with temperature, this is indistinguishable from trends reported from previous studies on foraminiferal calcite. However, no correlation is found when EPS was absent from the solution (Fig. 1b). This indicates that trace element incorporation will vary between sites of identical Mg/Ca_{water} and temperature but differing ionic strength. Equally, changes in ions not directly incorporated into calcite can alter trace element ratios within a site spatially and temporally when biofilm masses are present.

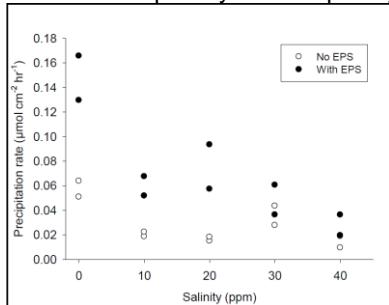


Figure 2. Calcite precipitation rate in sterile experiments in the presence and absence of EPS

Experiments where EPS concentrations were varied show that precipitation rate decreases with increased EPS presence (Fig. 3a), reflecting binding of ions in solution and blocking of step edges on the crystal surface. $(\text{Mg}/\text{Ca})_{\text{calcite}}$ increases in a linear fashion in freshwater solutions with increasing EPS levels (Fig. 3b). This reflects the tendency to very Mg-poor calcite at fast growth rate previously noticed in living biofilm experiments.

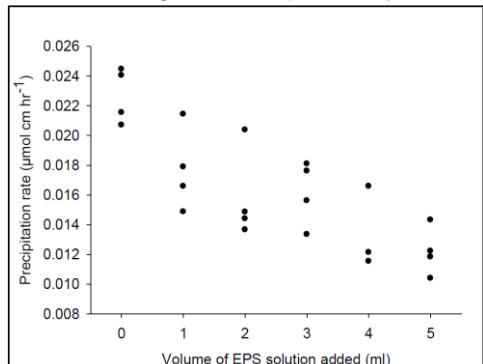
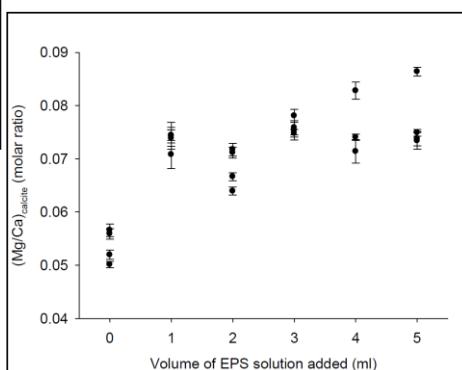


Figure 3. Response of calcite deposition to variable EPS addition in terms of a) left, precipitation rate and b) right, Mg/Ca_{calcite}.



The role of bacteria in the generation and biodegradation of petroleum

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Since the early 1980s, it is known that bacteria contribute a considerable part of the petroleum reserves. Bacteria are beings that researchers began to understand better in the last 20 years. They are beings with cells (procaryotes) different from the cell of most photosynthetic organisms (eucaryotes). Bacteria play an important role in the generation of petroleum, by attacking the newly formed kerogen. Can bacteria produce petroleum only by themselves, without any contribution from photosynthetic organisms? Possibly no, possibly yes. Bacteria contain a "suicide" gene, by which they can control their population in times of nutrition scarcity available. Bacteria produce a new generation every 20 minutes, as their DNA is easier to divide. If one wishes to kill a bacterium, it has to be burned. Extremophilic bacteria may live under extreme heat, or cold and are suspected to exist on the planet Mars.

Deep biodegradation of petroleum is now an accepted reason to explain the heavy oils in deep reservoirs. Petroleum microbiology teaches that bacteria may survive by mitosis for hundreds of millions of years. Certain bacteria may create new petroleum and others may destroy it.



'Giant microbialites': from thrombolites to stromatolites and back again. Upper Miocene, Mallorca (Spain)

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The term '*giant microbialites*', although relatively vague, has been commonly used for describing modern Bahamian stromatolites up to 2.5 m high, as well as other modern and ancient m-scale microbialites. Here we present a preliminary study of exceptionally well-exposed Upper Miocene '*giant*' microbialites (Fig. 1) with a remarkable variety of macro-, meso- and micro-structures (Figs. 1-3).



These microbialites crop out at Porto Pi, near the Palma harbour (Mallorca, Spain). They are late Miocene in age and belong to the Santanyí Limestone, a lithostratigraphic unit time-equivalent to the Tortonian-Messinian Reef Complex. The studied deposits (Fig. 1) are underlaid and overlaid by reefal carbonates, and they include: 1) A *lower microbialite bed* (~7 m thick) with '*giant*' ovate domes, up to 6 m wide and 6 m high. 2) An *upper microbialite bed* (~0.6 m thick) with smaller domes 0.2-2 m wide and <0.5 m high. Most of these deposits are mainly composed of dolomiticrite.

The *lower microbialite domes* consist of a thick (<4 m) core with clotted mesostructure (i.e. thrombolitic), and a thinner (<2 m) upper part with laminated stromatolitic mesostructure (Fig. 1). The stromatolites grade upwards from finely- to poorly-laminated with common breccia layers and calcite pseudomorphs after evaporites. The inter-dome sediments, in their lower part, consist of fine-grained peloidal-silty packstone-grainstone with wave and climbing ripples and wavy and flaser bedding, which is interfingered with the finely-laminated stromatolites. Locally, mud-cracks and dm-sized nodules with calcite pseudomorphs occur. Towards the top, the inter-dome sediment is coarser intraclast-breccia and peloidal-bioclastic grainstone. The *upper microbialite domes* are smaller (Fig. 2) but they have similar structure: thrombolitic cores and thinner (~20 cm) stromatolitic outer parts (Fig. 2). Here, the inter-dome sediment is cross-bedded peloidal-silty packstone-grainstone, with *Thalassinoides*-like traces. All these features indicate shallow wave- and tide-influenced restricted marine conditions, and although it may be tempting to link them to the Messinian salinity crisis, the regional stratigraphic context indicates that these microbialites predate the sea-level fall that triggered the Messinian crisis.

Microstructures of the thrombolites consist of dolomiticrite clots creating an open fabric with wide irregular pores filled either by grains or by late calcite cement (Fig. 3A). Stromatolite laminae consist of clotted-peloidal dolomiticrite with abundant peloids, silt-sized quartz and minor ooids (Fig. 3B). Locally, dendritic shrubs, both micritic and filled by late calcite cement, occur in the laminae (Figs. 3B-C).

Coexisting thrombolitic and stromatolitic mesostructures, reported in other Miocene successions, have been attributed to changes in water depth. Nevertheless, the sharp thrombolite-stromatolite transition within the Porto Pi domes (Figs. 1-2) indicates a striking

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change that may have been controlled by biotic factors, in addition to changes in water depth (e.g. subtidal to intertidal transition). This mesostructure transition, together with the coexistence of contrasting microfabrics (clotted, agglutinated, microbial shrubs), make the Porto Pi microbialites exceptional and suggest that their study may provide interesting insights into the role of microbes in forming and interacting with sediments.

Acknowledgements: Funded by projects CGL2013-42867-P, E-28 (Unizar-Aragón Government) and CGL2014-52670-P, and by a post-doctoral fellowship of the Alexander von Humboldt Foundation.



Figure 1. Outcrop of the studied microbialite deposits.

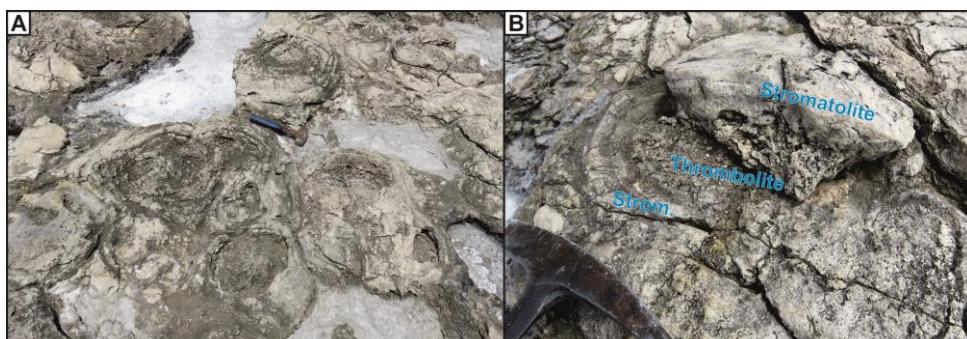


Figure 2. A: Top view of the *upper microbialite bed*. B: Detail of one of the domes of the bed.

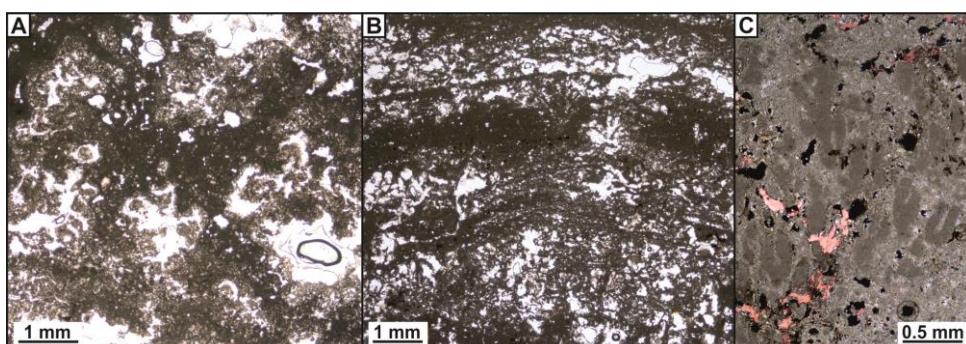


Figure 3. A: Microfabric of thrombolites. B: Microfabric of stromatolites. Note dendritic shrubs filled by cement. C: Micritic dendritic shrubs. Alizarin Red S stained. Crossed Nicols.

Mineral precipitates in modern microbial mats: crystallites, spheroids, bacteria, vesicles and viruses

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Reports of dolomite occurring within microbial mats relate precipitation to microbial activities and associated EPS (mucilage). Other minerals precipitated include calcite (low-Mg, high-Mg, very high-Mg), aragonite, Fe and Mn Ca-carbonates, clay minerals and pyrite. In modern high-intertidal microbial mats from Qatar, TEM analysis shows mineral precipitation beginning in the topmost layer with an amorphous Mg-Si-Ca material forming within EPS around bacteria. With time and depth of burial within the mat, this develops into Mg-Si clay fibres and Ca-Mg-CO₃ crystallites. Calcite crystallites grow from a nano-point of nucleation to form conical bundles, splaying out 20-30°. Growth in two or more directions leads to dumbbell and stellate structures. Cones develop a triangular and then hexagonal shape, and eventually terminations form to give nail-head-type (rhombohedral) calcite crystals, 5-30 microns in length. Spheroidal structures within the mat vary from perfect spheres to more commonly being imperfect, almost with flat sides and edges, in some cases coalescing to form compound structures. There appear to be 2 sizes, nano-scale spheroids and micron-scale spheroids. The larger spheroids (0.5-2 microns, 'micropearls') could well be permineralised bacterial-algal cells, or coccoid bacteria themselves, whereas smaller ones (10s-100s of nm) may be permineralised bacterial vesicles or viruses, or simply the initial amorphous precipitates. Lower in the mat, felted layers of palygorskite-type fibres have an undulating, sheet-like form, similar to EPS. In the Qatar mat dolomite is present as micron-sized rhombs. The source of silica for the Mg-silicates could be wind-blown dust or diatoms, and the Mg-Ca is likely from seawater. Silica dissolution-Mg silicate precipitation, and carbonate precipitation, are likely to have been driven by pH-Si-redox changes within the mat, related to micro-environmental changes induced by the microbes and their (+EPS) degradation.



Pilbara Oddities

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Three bedding surface features exposed in the BIF Brockman Iron Formation, Hamersley Group (late Archaean) in Kalamina Gorge, Karijini National Park, Pilbara, Western Australia indicate modification of biofilms associated with Trendall microbands.

Three distinct modifications have been recognised. Two have been interpreted as *reversed synaereses* and *setulfs* (inverted *flutes*).

A third, *Gamma* (Willey 2014), is typically seen on bedding surfaces as sub-circular depressed zones (*cheramos*, -*oi*¹), with radiating **spokes** (*kneme*, -*ai*¹). Several occur on one bedding plane, with localised concentration up to about 400/m². They range from 17mmx15mm up to 52mmx38mm. The largest *cheramos* – has 25 *knemai*; it also has a clear **crenulated circular crack** (*halos*, -*oi*) around the *cheramos* with a diameter slightly more than double that of the *cheramos*. *Halos* has only been seen in one other *cheramos*, suggesting the *haloi* are only developed at the topmost level. The terms *cheramos*, *kneme* and *halos* are introduced to avoid the use of vernacular words for features, which have as yet unknown origin. The combination of the *cheramos* surrounded by *knemai* gives *Gamma* a pseudo-medusoid appearance; the *knemai* of closely located *cheramoi* run into each other.

The *cheramoi* are zones within which the composition of several subjacent microbands have been reduced in thickness and chemically modified to microbanded chert (senso Trendall & Brockley 1970). Within the *cheramoi* the thickness of the microbanded chert is 25% of the adjacent unmodified Trendall microbands outside the *cheramoi*; this reduction in thickness reflects the removal of, or failure to deposit, the iron component of the classic Trendall microband; Trendall & Brockley (1970) calculated this as about one seventh. The *cheramoi* have stratigraphic depth (up to 37 Trendall microbands or about 50mm); on bedding surfaces, their appearance varies from marked depressions close to their top, to raised domes at their base.

'Medusoid' appearance is a feature of 'Astropolithon'(s.l.) – a gas/fluid escape feature in microbial mats involving upward entrainment of sediment. No entrainment features are seen in *Gamma*.

Gerdes (Fig.2-1-4H in Schieber 2007) illustrated modern features with geometry comparable to *Gamma*; her caption reads: "Individual knots protruding out of the leathery surface mat. Major species involved in both mat and knots is cyanobacterium *Lyngbya aestaurii* ." Gerdes's figure shows lines/strands (?spokes) connecting neighbouring knots.

Regardless of modern analogies, *Gamma* either destroyed or inhibited development of the normal microbe-bound microbands. Timing of this is uncertain; however, the *spokes* suggest completion when the topmost layer was still the depositional interface, with *spokes* representing surface tension tears in the microbial mat around *Gamma*'s depressions, and *haloi* representing some boundary in extracellular polymeric materials. The relationship between *Gamma* and the microbands could be seen as competition between bacteria each influencing the sedimentary record differently.

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Biofilm origin of clay coated sand grains and sediment heterogeneity within estuarine systems

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Clay-coated sand grains have been shown in both oilfield-core- and laboratory-based studies to be one of the main causes of anomalously high porosity in deeply buried sandstone reservoirs. The current uncertain cause of clay material attachment and preservation upon sand grain surfaces is one of the key limiting factors in predictive models. Here we report a new biofilm mediated mechanism that explains clay material attachment to sand grain surfaces and produces detrital clay coats, which on burial recrystallization produce coatings capable of inhibiting porosity-occluding quartz cement. The study has also started to reveal the extent to which diatom-derived biofilms influence the distribution of sediment heterogeneity (grain size and clay fraction) within an estuarine system.

This study adopted a high resolution analogue methodology, focused on the Ravenglass Estuary, UK. The work involved a combination of fieldwork, sediment characterisation, scanning electron microscopy, environmental scanning electron microscopy, automated SEM-EDS microscopy, biomarker analysis (chlorophyll-a), phenol-sulfuric assay (bound carbohydrate) and Raman spectroscopy techniques. Analyses were employed to characterise the distribution patterns of clay grain coats and biofilm distribution within surface and core sediment samples.

Our study shows that clay-coats primarily result from adhesive biofilms within modern marginal marine systems. Our work has shown that biofilms derive largely from diatoms. We propose a mechanism by which biofilm distribution controls the occurrence of clay-coated sand grains and clay fraction within estuarine settings. We further advocate, because sandy sediments are derived from marginal marine settings, that clay material and coats can be transported out into deeper water clastic depositional systems. This diatom-induced bio-mineral interaction potentially revolutionises the understanding of clay-coated sand grains and offers a crucial first step to prediction in ancient and deeply buried sandstones.



Carbonates in hyper-alkaline settings: lessons from modern systems and implications for South Atlantic “Microbialites”

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Microbial communities may be ubiquitous in many sedimentary environments but do not necessarily impact on the products of those environments. To illustrate this we compare carbonates from two hyper-alkaline settings: the Cretaceous lacustrine Barra Velha Fm reservoirs, offshore Brazil (known as the “Microbialites”), and active tufa-travertines from lime kiln waste seepages. The former have been interpreted as abiotic precipitates in hyper-alkaline evaporitic lakes but some companies operating in the region still invoke a microbial origin for the thick (up to 550m) formation. Rare microbialites do occur in the formation, with prominent filament moulds but are restricted to near the top of the formation where there is evidence of changing lake water chemistries. However, in the bulk of the formation the main components are mm-cm-sized “crystal shrubs” and mm-sized calcite spherulites, lacking in filaments and any evidence of endolithic effects. Micritic carbonates and obvious precipitates such as pore-filling cements and ooids are rare to absent. What is known is that the carbonates formed during evaporitic phases in shallow lakes after the precipitation of Mg-silicate (Wright & Barnett, 2015; Wright & Tosca, 2016). The pH during carbonate precipitation likely exceeded 9. If microbes were present their activities were greatly reduced leaving no evidence of any involvement during carbonate formation.

Comparisons can be made with some hyper-alkaline travertine/tufa deposits associated with lime kiln waste such as in Foel Fawr, South Wales (Emery, 2013). Here analysis of the fabrics associated with a range of environments highlights the importance of physico-chemical precipitation in the system and proximal facies are dominated by abiotic fabrics, while distal and marginal facies show an increasing degree of biological influence as the pH decreases. In the proximal setting, with average pH 11, mm-sized crystal shrubs develop, lacking any evidence of microbial involvement.

At high pH levels and carbonate saturations microbial activity is reduced while high precipitation rates favour abiotic carbonates, overwhelming any microbial contribution. With respect to cyanobacteria the high hydroxide concentration consumes dissolved CO₂ reducing its bioavailability and making photosynthesis difficult. On Foel Fawr, cyanobacteria are excluded from proximal environments by the low pCO₂. The principal difficulty for prokaryotes living in hyper-alkaline environments is the need to maintain a neutral cytoplasmic pH (Konhauser, 2006). This is typically achieved with the use of a Na+/H⁺ (or K+/H⁺) antiporters and adaptations to increase cytoplasmic proton retention (Krulwich et al., 1997; Padan et al., 2005).

In the case of the Barra Velha, where evaporation triggered carbonate precipitation, CO₂ degassing, driven by solubility decreases with evaporation, drove up pH and CO₃²⁻ but coupled with low Ca²⁺ still favoured CaCO₃ crystal growth, the kinetics of which were inhibited at very high pH (Ruiz-Agudo et al., 2011). This favoured an increase in crystal size over new nuclei, explaining the lack of other precipitates (e.g. micrite). The lakes were low in sulphates and chlorides with little evidence that early sulphate reduction occurred during carbonate precipitation.



While we cannot rule out all microbial-carbonate interactions, the reconstructed chemical evolution of the Barra Velha lakes, and comparisons with modern hyper-alkaline carbonates, strongly suggests that the thick so-called “Microbialite” reservoirs of Santos Basin were abiotically produced. The microbial paradigm does not apply in all carbonate systems. The use of the term microbialite for the Barra Velha carbonates has led to the development of erroneous seismic and facies models for the reservoirs, and serves as an example of Schumm’s (1991) warning of the dangers of “name magic” whereby “*If we give something a name we often think that we understand it.*”

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Microbial, biotic or not? Spherulitic calcites and the critical role of Mg-silicate hosts

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There is an ongoing debate about the origin of calcite spherulites triggered by their abundance in the Cretaceous Pre-Salt lacustrine carbonates of the South Atlantic, such as the thick (locally >550m) Barra Velha Fm. of Santos Basin. In this unit the mm-sized (up to 13mm), low Mg-calcite spherulites occur within metre-scale evaporitic cyclothems. They have been interpreted (Wright & Barnett 2015) as having grown abiotically in Mg-silicate gels in shallow hyper-alkaline lakes, and Wright & Tosca (2016) provided a geochemical model to explain their occurrence and mineralogy. Recently Mercedes-Martín et al. (2016) have questioned the viability of calcite spherulites growing abiotically in Mg silicate gels, favouring formation in lakes with organic acids in solution, whereby Mg-rich phases would have limited calcite precipitation. Their experiments produced sheet-like stevensite crystals rather than a gel.

We present textural evidence from the Barra Velha Fm. showing the relationship between spherulite nucleation and growth and Mg-silicate matrices. In addition, in situ spherulites are only found in a Mg-silicate matrix (see figures), or where this matrix was dissolved or dolomite-replaced, and although the spherulites were commonly reworked, no reworked Mg-clays occur in the succession. This is best explained as during reworking the gels would have been dispersed into the water column, and where not reworked the crystalline clays formed from the gels, during burial. These observations are in accord with extensive experimental evidence, conducted across a wide range of chemical conditions, that solutions supersaturated with respect to Mg-silicates: (1) commonly produce hydrated nano-crystalline gels and (2) upon dehydration, dehydration of the Mg-silicate gels triggers re-ordering and formation of crystalline Mg-silicates (i.e., stevensite, kerolite, and sepiolite) (Tosca et al., 2011; Tosca & Masterson, 2014; Tosca, 2016; Tutolo & Tosca, 2016). The unusual pseudo-fenestral pores and diagenesis seen in the Barra Velha Fm. are also explained by the breakdown of former extensive Mg silicate matrices (Wright & Barnett, 2015; Tosca & Wright, 2015).

As regards the suggestion that high concentrations of Mg, required for Mg silicate formation, inhibited calcite formation, this has been addressed in the geochemical models for the Barra Velha Fm. (Wright & Tosca, 2016) which show that calcium carbonate nucleation would not have occurred until the precipitation of Mg silicates had largely ceased, depleting the concentration of Mg and favouring the formation of calcite (not HMC or aragonite), as is seen in the Barra Velha Fm. In addition, although Mg/Ca ratio plays a well-established role in the determination of CaCO_3 polymorph selection, we note that the kinetic effects of inhibiting chemical species, in particular, dissolved $\text{SiO}_2(\text{aq})$ during crystallization is poorly studied at very high pH. Furthermore, recent experimental evidence suggests that the nucleation of Mg-silicates and CaCO_3 polymorphs appear to be linked, whereby the nucleation of one phase commonly results in the heterogeneous nucleation of the other (Tutolo & Tosca, 2016).

While we do not dispute that organic acids and other biotic influences can lead to calcite spherulite growth in many situations, the extensive textural evidence from the Barra Velha Fm. is that there was a close relationship between Mg silicates and spherulite growth. The spherulites nucleated and grew within a precursor Mg silicate gel. Mercedes-Martín et al.

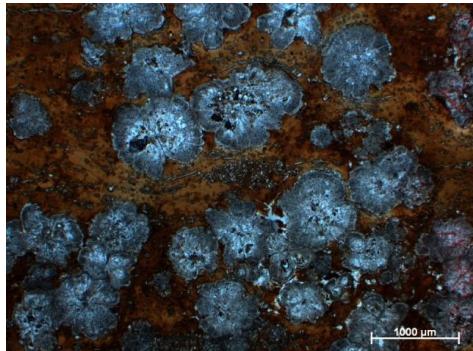


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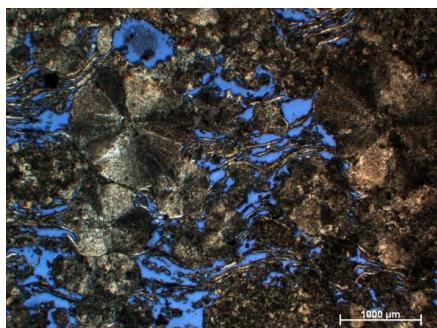
(2016) state that “ clay-gels are not required to form voluminous deposits of spherulitic grains in Phanerozoic lacustrine environments” but the evidence from the Barra Velha Fm., the unit which has stimulated the debate, is clear.

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Spherulites within talc-stevensite matrix with “floating” dolomite rhombs and “bridges” within the matrix.



After dissolution of matrix during diagenesis. Note he dolomites and “bridges” now within porosity.

Yellow aragonite cement in methane-seep deposits results from biofilm mineralization

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Ancient and modern methane-seep deposits represent exceptional carbonate archives of microbial activity. Metabolic processes such as sulfate-driven anaerobic oxidation of methane (AOM) by methanotrophic archaea and sulfate-reducing bacteria are recorded in these limestones within carbonate phases, including the microcrystalline rock matrix and cements. The early diagenetic cements are composed of aragonite and calcite, and can be readily distinguished from later diagenetic cements. Two common early diagenetic phases are clear and yellow aragonite, both resulting from AOM. Although phase-specific studies on C and O stable isotopes have confirmed that both phases originate by the same process, their mode of precipitation is different. We document that yellow aragonite cement precipitates at hotspots of AOM activity, whereas clear aragonite forms at some distance from such hotspots after diffusion of carbonate ions produced by AOM, and put forward that yellow aragonite cement represents fossilized biofilms. Remarkably, yellow aragonite cement is rich in strongly $\delta^{13}\text{C}$ -depleted lipid biomarkers of the AOM-performing communities; the same biomarkers are almost absent in clear aragonite. Phase-specific trace and rare-earth element (REE) analyses on four ancient seep deposits reveal that some of the yellow aragonite cements are characterized by a relative enrichment of light REEs relative to heavy REEs – an uncommon pattern for marine carbonates. The fact that light REEs are preferentially adsorbed and passively enriched in living and dead organic matter strengthens the notion that yellow aragonite cement results from biofilm mineralization. The presence of light REE enrichment in the analyzed samples is associated with very low Mg/Sr ratios, suggesting that the preservation of this specific signature depends on the degree of recrystallization of aragonite into calcite. Consequently, only the most pristine seep limestones archive the patterns diagnostic for mineralization within AOM biofilms.



Burlington House **Fire Safety Information**

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation.
Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:

Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre

Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance

Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS.**

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

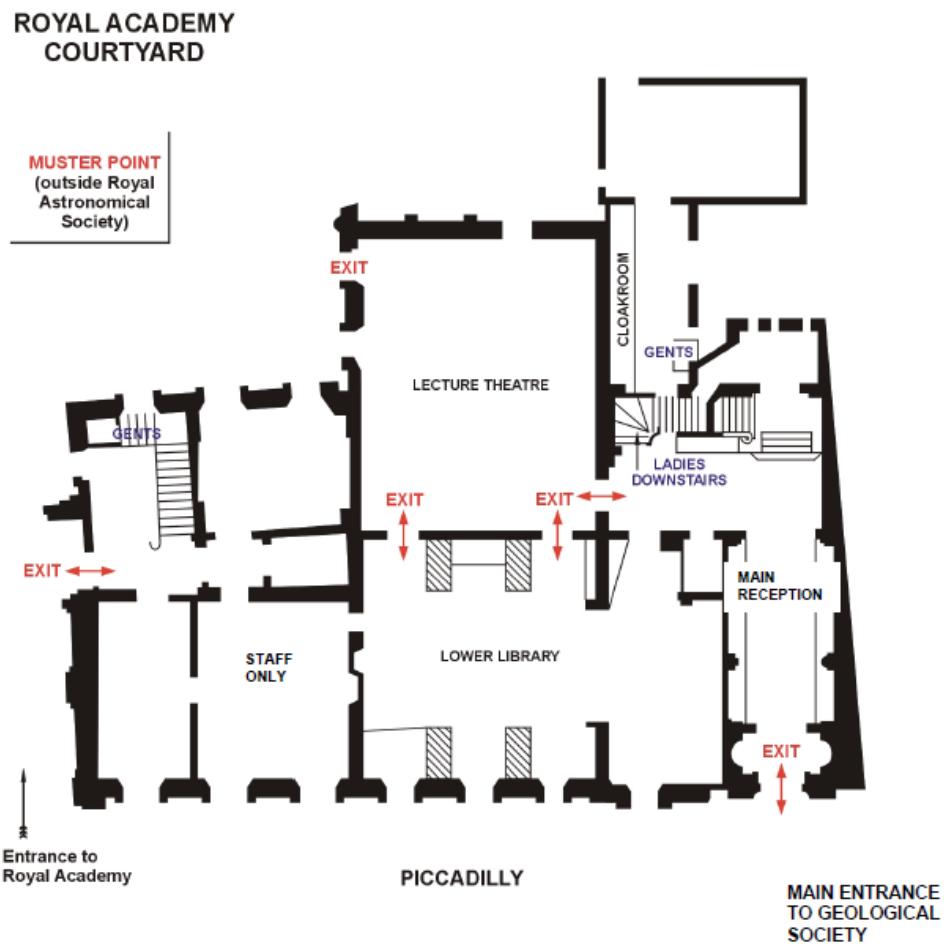
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.



Ground Floor Plan of The Geological Society, London, Piccadilly



Lyell Meeting 2017: Sticking Together: microbes and their role in forming sediments



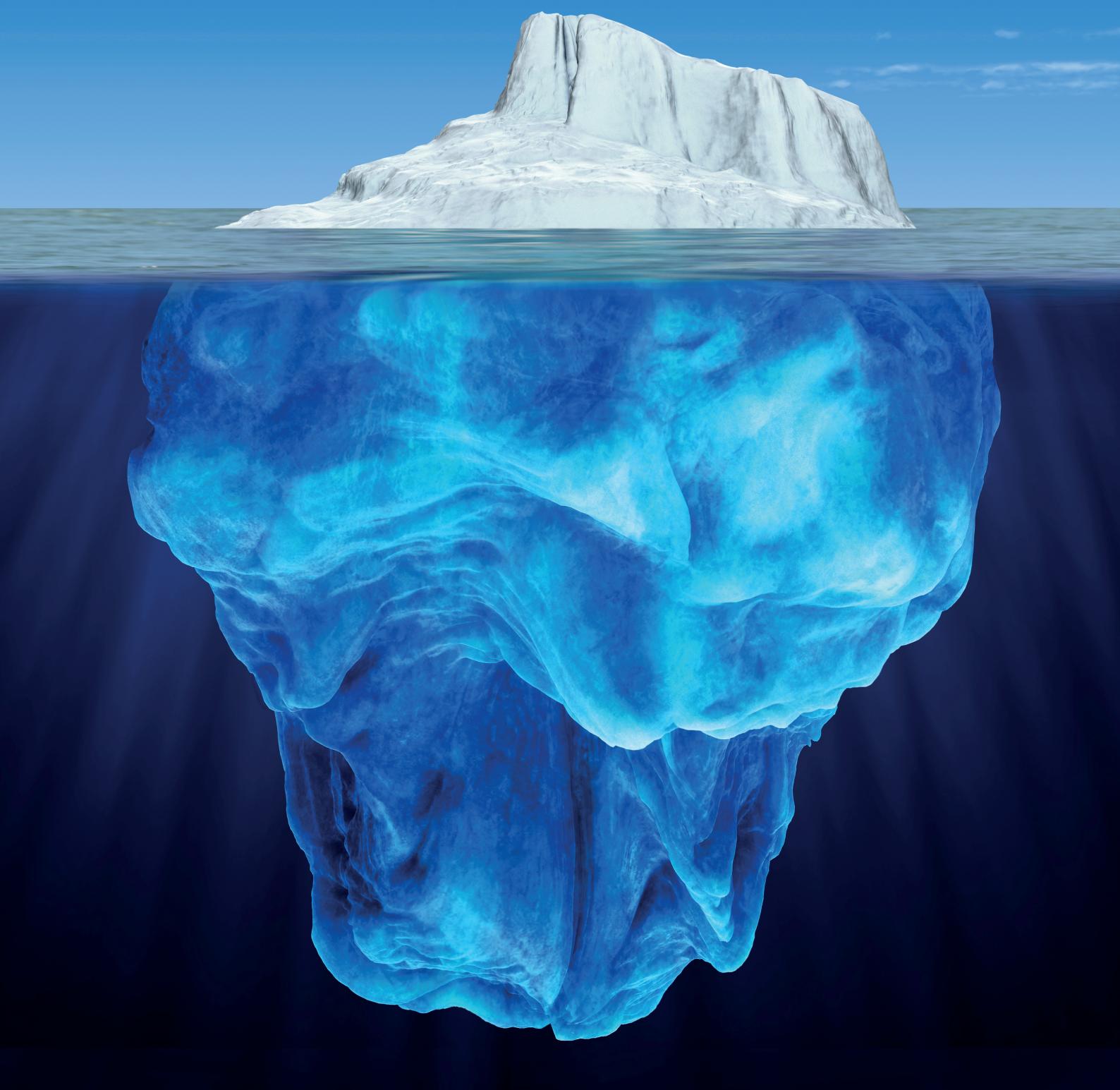
2017 Geological Society Conferences

15 March	GSL London Lecture – Paleobiomechanics and the evolution of fossil vertebrates	Burlington House
22-23 March	Subsurface Sand and Remobilization and Injection	Burlington House
12 April	GSL London Lecture – Space rocks, rockets and robots – Exploring our Solar System today and tomorrow	Burlington House
24 May	GSL London Lecture – Inequality in global earthquake risk today	Burlington House
28 June	GSL London Lecture – Sink holes – collapsing houses, Alice and Wonderland and witches	Burlington House
10-12 July	Managing Risks across the Mining and Oil and Gas Life Cycle	Imperial College, London
13-14 July	Sharing an Uncertain World: Lessons in Managing Risk	Burlington House
7-8 September	Building Resilience	Burlington House
13 September	GSL London Lecture – ‘Not under my backyard’: are public perceptions of the risk of geological engineering projects well-founded?	Burlington House
14-15 September	The evolution of flooding and flood risk: past, present and future	Burlington House
25-27 September	Fermor Meeting 2017: Factory Earth	Burlington House
3-5 October	William Smith Meeting 2017: Plate Tectonics at 50	Burlington House
16 October	6 th UK Deep Geothermal Symposum	Burlington House
18 October	GSL London Lecture – The importance of fault interactions in the growth of fault systems and its implications for earthquake hazard and risk assessment	Burlington House
26-27 October	Ground related Risk to Transportation Infrastructure	Burlington House
31 October – 2 November	Fold and Thrust Belts: Structural style, evolution and exploration	Burlington House
6-7 November	Janet Watson 2017 Meeting: Title TBC	Burlington House
8 November	GSL Nottingham Career and Industry Day	British Geological Survey, Keyworth
15-17 November	Handling Fault Seals, Baffles, Barriers and Conduits	Burlington House
22 November	GSL London Lecture – Why Earth developed into the crucible of life, and Venus into a hostile wasteland	Burlington House
22 November	GSL Edinburgh Career and Industry Day	Our Dynamic Earth, Edinburgh
23 November	Bryan Lovell 2017 Meeting: Title TBC	Burlington House
27-28 November	PG: Cross-border Exploration between UK and Norway	Burlington House
11 December	GSL London Lecture – Dangerous Neighbours: Living with volcano risk	Burlington House



Tiny Samples - Big Results

Sub-100 µg carbon upon consultation



Radiocarbon Dating
Consistent Accuracy, Delivered on Time

