SEPM Field Conference

Microbial Mats in Siliciclastic Deposits (Archean to Today)

May 21st to 23rd
Denver, Colorado, USA

Nora Noffke & Henry Chafetz
Dear Authors,

Welcome to our conference on microbial mats in sandy deposits! You all have submitted very interesting papers that will enable us to explore a wide range of topics in this still novel research field. We hope that this conference sparks spirited discussions and suggests directions of future development.

The conference is a community effort. We welcome all input from you the participants. Whereas the meeting is intended to enable networking and provide a forum for exchange of ideas, an additionally aim is to produce a first rate SEPM special publication. Please consider submitting a manuscript as soon as possible. Even if you or colleagues cannot attend this meeting, you are invited to send in your manuscript. We will ask every author or group of co-authors to review one manuscript. This will facilitate the progress of this special publication.

The absolute deadline of submissions is June 30th 2010. We will be unable to accept any manuscript after this deadline, and no exceptions can be made.

If possible, please restrict your manuscript to 10 printed pages (35 manuscript pages including figures, references, acknowledgments). Please follow the author guidelines published on the SEPM web page. Palaios and Journal of Sedimentary Research also follow these guidelines. We will not be able to provide any support in formatting your manuscript.

The logistics of the conference will be organized by SEPM headquarters. Our warmest thanks for this effort to all staff, especially Theresa Scott, Michele Thomson, and Howard Harper. Any questions you have for registration, accommodation, or transport please direct to SEPM. Any questions regarding the scientific program and the publication please direct to us.

Make sure to monitor the SEPM conference web page for updates. We will not be able to contact every author individually. The web page will shortly display required information on registration, hotel address, and venue details.

Please forward this message and all following messages to all of your co-authors.

We look forward to this conference, and to meet you in Denver!

Nora Noffke
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Cyanobacteria mats in the sandy soils in the east coast of India and their ecophysiological implications.

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Abstract

Cyanobacterial components in the mats/biofilms occurring in the top soil as well as up to 30 cm below the sandy soil cover near Ramchandi, at the Bay of Bengal coast, India was investigated. These soils showed wide variation in their nutrient content, pH and salinity levels. The mats on the top layer of the soil harbored 14 cyanobacterial species belonging to the genera *Anabaena*, *Calothrix*, *Nostoc*, *Westiellopsis*, *Fischerella*, *Plectonema* and *Microcoleus*, though occasionally certain green algae and diatoms also occurred especially in the rainy season, hence were not the major components of these mats. Two distinct mat forming cyanobacteria, *Microcoleus vaginatus* and *Nostoc paludosum* on the sandy soils were most tolerant to a wider pH range, *Westiellopsis prolifica* preferred alkaline pH where as *Plectonema puteale* was very sensitive to changes of the pH to acidic or alkaline range. However, upon their growth almost all of them changed the pH of the culture medium towards alkaline side, and those grew at pH 10-11, decreased the pH of the medium close to 9 suggesting their influence on soil conditioning making it to buffer between 7 to 9 at which it is conducive for cyanobacterial colonization. Further it was observed that the organism which occurred more prominently penetrating several centimeters below the top soil of the coastal zone and those having distinct sheath layer around their trichome tend to be comparatively higher tolerant to NaCl.
Unusual hydrodynamical behaviour of living oncolites, northern Kuwait

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Abstract

Microbially-induced sedimentary structures, including siliciclastic oncolites, have been discovered along a prograding peritidal coastline in Kuwait. The area lies south of the depositional basin of the Tigris-Euphrates estuary (Figure 1). Oncolites are forming in a shallow sub-tidal to intertidal environment with locally excessive hydraulic energy, leading to cyclic sedimentation, and lag deposits occur at depth within the tidal creeks (Figure 2). Multidirectional ripple marks document a series of erosion events interfering with microbial stabilization in lower subtidal settings. Oncolites morphologies are numerous and varied (Figure 3): clotted, spherical, disc/rounded, platelets, and conical, and they are often coated with sand. Quantitative analysis of Corey Shape Factor reveal 2 distinct populations but there is local overlap. A plot of the Equivalent Diameter vs. Corey Shape Factor (Figure 4) provides the best indicator of the relationships within the total population, which occur on a smooth curve, indicating an overall hydrodynamical linkage between the oncolite classes. The unique environment is located between migrating sand bars within deflating nebkha dunes. Figure 5 is a block diagram relating the various factors that have contributed to the morphological spectrum of the oncolites. This is a preliminary set of results for living oncolites.
Morphologically distinct ferromanganese stromatolites in lacustrine sediments from the headwaters of the Connecticut River, New Hampshire USA: Promising evidence for microbial activity

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Abstract
Fossil microbialites abound from the Archean Eon (>3.5 Gya) through the Holocene. They provide a major source of information about early life on Earth and potentially about life on other planets. We discovered ferromanganese stromatolites in Second Connecticut and Third Connecticut Lakes (2CTL and 3CTL, respectively), two of the four headwater lakes of the Connecticut River, Pittsburg, New Hampshire, USA. Such structures, known from the literature, are called nodules, concretions, thrombolites, ooliths, metalliferous sediments and many other terms. Ours are geographically extensive (e.g., area of 9,000 m² in 2CTL) and subaqueous (3-15 m water depth) at the sediment/water interface. Since they are both laminated and show strong evidence of microbial activity we adopt the term “stromatolites” after Kalkowsky (1908). The ferromanganese stromatolites found in these lake form irregular but concentric rings around a central “nucleus” such as a pebble or cobble. Although similar structures are described in freshwater systems (e.g. Lake Oneida, New York and Lake Vermillion, Minnesota) the others lack the variety of morphologies, range of size distribution and continuous pavement coverage of those in the New Hampshire lakes. None has been reported from any of the six New England States. Comparable freshwater stromatolites range from 5 to 20 cm in diameter whereas our pustulate, lattice, chimney, concentric rings and other morphologies measure up to 43 cm (Asikainen and Werle, 2007). Scanning electron and microprobe imagery show abundant microbial remains that coat both external and internal surfaces of the laminae of the structures. Filamentous, rod and coccoid morphotypes, presumably bacterial algae components of biofilms extensively encrusted with manganese and iron oxides were seen.

References:
Sedimentary features associated with mats of chemotrophic sulfur bacteria


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Ancient wrinkle structures are commonly associated with phototrophic microorganisms because of their similarity to textures that result from biostabilization of sediments by cyanobacteria in modern environments. However, mats of chemotrophic bacteria also commonly trap and bind siliciclastic sediments and produce sedimentary fabrics similar to those created by cyanobacteria. Mats composed of the sulfur-oxidizing bacteria Beggiatoa and Thiomargarita from the Gulf of Mexico and Costa Rica Margin exhibit sediment trapping and binding, resulting in wrinkled surface textures similar to those observed on bedding plane surfaces in ancient rocks. These observations suggest that in the absence of evidence, microbially-induced sedimentary structures should not be tacitly assumed to record the activities of phototrophic organisms.
The recognition of microbiolaminations, corrugation (or wrinkle) marks, and microbiocracks in siliciclastics, considered here expressions of “microbially induced sedimentary structures” (MISS), is in its infancy in Brazil. We offer five study cases in siliciclastics for the present discussions: “Lenheiro Cycle” (intertidal, Neoproterozoic), Pimenteira Fm (stormy shallow marine, Devonian), Sergi Fm (eolian, Jurassic), “Caruaçu Beds” (rift lake, Cretaceous) and Tremembé Fm (rift lake, Paleogene). (1) The “Lenheiro Cycle” is a regressive cycle belonging to the neoproterozoic Carandai Basin (Ribeira Belt, Southeastern Brazil), characterized by sandstones and mudstones deposited in tidally influenced coastal to fluvial paleoenvironments. Synaeresis cracks were once identified in its heterolithic facies, which are here reinterpreted as a true MISS, what allows a genetic reinterpretation of these facies as inter- to supratidal. (2) The Pimenteira Fm occurs in the Parnaíba Basin (Northern Brazil), and is characterized by shallow marine mudstones of a devonian epeiric sea that flooded the northern Gondwana. The mudstones are interbedded with very fine to fine, hummocky cross-bedded sandstones, where corrugation marks were found atop these storm beds (tempestites). This unusual occurrence of ancient microbial mats points to another opportunistic colonizer under fair weather condition that followed marine storms. (3) The Sergi Fm is an expression of the fluvio-eolian sandstone depositional systems that characterizes the late jurassic Pre-rift Phase (Gondwana breakage) of the aulacogenic Recôncavo Basin (Northeastern Brazil). The identification of corrugation marks, microbiocracks, and mud curls (considered here a true MISS) in the inter-/extradune sandstone facies allows the proposition of a distinct wet eolian system. (4) The “Caruaçu Beds” (Maracangalha Fm) are thin to medium bedded turbidites interbedded with the mudstones of a deep(?) neocomian lake of the Rift Phase (Gondwana breakage) in the Recôncavo Basin. Microbiolaminations and corrugation marks (“elephant skin”) found in thinly ‘hemipelagic’ beds of the Caruaçu Beds point to the deposition of these fine muds under the photic zone, in shallower waters than they have been previously accepted, possibly in a delta front/plain. A recently surprising discovery of localized raindrop imprints associated to those MISS also support the interpretations. (5) Oligocene ‘pyrobituminous’ shales of the Tremembé Fm occur in a small onshore cenozoic ‘rift’ basin in Southeastern Brazil (Taubaté Basin), bordering the Santos Basin (Brazilian continental margin). Microfacies analysis (petrography) of these shales allowed the identification of microbiolaminations, what rendered, together with their palynofacies analysis, a distinct interpretation of a shallow hypersaline lake waters, contrasting to the traditional ‘deep rift lake’ point of view. Microbially induced sedimentary structures are promising proxies for a better definition of facies, paleoenvironments and the stratigraphic context of those occurrences in Brazil.
Deciphering the Cambrian Substrate Revolution

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Evidence from Precambrian carbonate (e.g., stromatolites) and siliciclastic (e.g., wrinkle structures) sedimentary structures indicates that in marine settings before the Cambrian conditions of seafloor environments were largely controlled by microbes and the mats which they form. During the Ediacaran-Cambrian transition a vertical component to marine bioturbation evolved, as well as overall increased seafloor bioturbation, which is called the “agronomic revolution”. These changes in bioturbation caused a decrease in the ability of seafloor microbes to form extensive subtidal mats that could be preserved in the stratigraphic record. The “Cambrian substrate revolution” (CSR) was originally proposed to encompass the evolutionary and ecological effects that occurred due to these substrate changes. This increase in bioturbation strongly altered biochemical and diagenetic reactions and redistributed sedimentary particles and pore water at the sediment-water interface. The continued evolution of bioturbating organisms also caused the development of a significant variety of new microenvironments, which led to the formation of new ecospace and evolutionary opportunities for other benthic organisms. Numerous studies have evaluated the “weird” morphology of early seafloor animals and how they adapted to an increasingly bioturbated substrate. Many early animals adapted to seafloors with strong microbial mat development are stem groups of the phyla we recognize today, and thus have morphological features absent in modern representatives. Crown groups of modern phyla first began to appear in the Cambrian and subsequently dominated Phanerozoic bioturbated seafloor environments. The CSR is thus a primary component of the Cambrian explosion. The CSR also represents the earliest-known example of allogenic ecosystem engineering by metazoans in the history of life.
The trace-fossil record of organism-matground interactions in space and time

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The study of trace fossils provides information on organism-substrate interactions. Ichnologic research has focused on biogenic structures emplaced in softgrounds, firmgrounds and hardgrounds. However, during the last decade a number of studies have started to explore the interactions between organisms and microbial matgrounds. Widespread matgrounds in both shallow- and deep-marine deposits during the Ediacaran provided substrates that were available for benthic colonization and the development of various interactions. The most abundant trace fossils in Ediacaran rocks are by far very simple grazing trails, such as *Helminthoidichnites*, *Helminthopsis* and *Gordia* (*Helminthopsis* ichnoguild). These trails are preserved either as negative or positive hyporeliefs/epireliefs, and are commonly associated with microbial mats, representing grazing of organic matter concentrated within microbial mats below a thin veneer of sediment. Grazing trails commonly crosscut corrugated surfaces resulting from microbial activity, without producing significant disruption. The *Helminthopsis* ichnoguild was not restricted to shallow-marine environments, but was also present in deep-marine deposits. In shallow-marine environments, interactions were also evidenced by the mollusk-like *Kimberella* and associated scratch marks (*Radulichnus*), produced by its paired radular teeth and preserved on microbial mats. While the vermiform grazing trails and the scratch marks record matground feeding by metazoans, interactions are also indicated for vendozoans, as reflected by serially repeated resting traces of *Dickinsonia* and the related genus *Yorgia* preserved on biomats. By the latest Ediacaran, simple burrow systems (treptinids) occur also in direct association with matgrounds. The replacement of matgrounds by mixgrounds (the “agronomic revolution” of Seilacher) was arguably the most significant change at ecosystem scale in the history of life. By the Early Cambrian, branched burrow systems became more complex and common (as illustrated by the appearance of *Treptichnus pedum*), resulting in increasing disruption of matgrounds in nearshore and offshore settings. While matgrounds were widespread in supratidal and upper- to middle- intertidal environments during most of the early Paleozoic, lower-intertidal deposits were already intensely bioturbated by the late Early Cambrian. The diachronic nature of the agronomic revolution is particularly evident in the deep sea, where microbial matground ecosystems persisted during most if not all the Cambrian. In addition to elements of the *Helminthopsis* ichnoguild, Cambrian deep-marine ichnofaunas also consist of arthropod trackways (e.g. *Diplichnites*) and more sophisticated feeding strategies represented by different *Oldhamia* ichnospecies, revealing complex architectural designs by undermat miners. In contrast, in deep-marine Lower Ordovician deposits, microbial textures are remarkably rare and patchy, and typically not associated with trace fossils. During the Early Ordovician the main lineages of deep-marine trace fossils (i.e., rosette, meandering, patterned, spiral) were established, resulting in the rise of the *Nereites* ichnofacies. Biomats persisted well into the late Paleozoic in the innermost, freshwater region of estuarine systems, as well as in fluvo-lacustrine deposits. Ichnofaunas dominated by very-shallow tier structures, such as arthropod trackways and grazing trails, locally associated with corrugated surfaces of microbial matground origin were common in these deposits. Comparative analysis of ichnofaunas in matgrounds provides evidence of the temporal and environmental restriction of biomats and allows a better understanding of animal-matground interactions, as well as of preservational biases in the trace-fossil record.
Bioturbation depth and microbially induced sedimentary structures in the Cambrian and Silurian of Sweden

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Microbially induced sedimentary structures, in the form of wrinkle structures preserved in fine-grained siliciclastic marine facies, occur in the Lower and Middle Cambrian and the Upper Silurian of Sweden. The Lower Cambrian cratonic succession starts with basal conglomerates and arkoses overlain by storm- and tidally influenced, inner shelf quartz arenite facies. In certain intervals, the latter facies exhibit intense bioturbation (Skolithos ichnofacies), most often with bioturbation index 5-6 in the uppermost ~0.3 m of thicker cross-stratified beds. Isolated traces (conveyor processing) may extend further below this zone. The maximum observed depth for the homogenised zone is 0.7 m in the Hardeberga Sandstone Formation, which is extraordinary for the Cambrian (cf. Droser and Bottjer 1988). Wrinkle structures have not been reported from this formation but occur in the basal beds of the overlying Norretorp Member of the Laeså Formation, which represent a sediment-starved subtidal setting with mica-rich, phosphoritic siltstone and fine-grained sandstone. Wrinkle structures, and possible palimpsest ripples, also occur in upper Lower Cambrian current-rippled, heterolitic shale-sandstone facies of the basal Mickwitzia Sandstone Member (File Haidar Formation). Due to prolonged transgression the Furongian is extremely starved of sediments and organic-rich alum shale progressively spread across the basin. From this time interval, trace fossils and wrinkle structures can be studied only in the rare preserved occurrences of shallow subtidal silt- and fine-grained sandstone facies that fringed the deeper shale basin. One such occurrence is represented by the Middle Cambrian Äleklinta Member (Paradoxissimus Siltstone) of the Borgholm Formation, which yields well-developed wrinkle structures at several levels. Here, individual and continuous biomat-horizons can be followed laterally for tens of metres. In common for the Cambrian occurrences of wrinkle structures in the basin is preservation at the top of thin sandstone beds without or with little evidence of epichnial and/or endichnial traces. The beds are interbedded with shale or mudstone and commonly yield abundant sole marks and hypichnial traces of the Cruziana ichnofacies. Wrinkle structures associated with Skolithos ichnofacies has not yet been demonstrated from Sweden, although it should be stressed that very little or no research has been conducted in this emerging field. The Ordovician of the basin is largely developed as temperate limestone facies and post-Cambrian wrinkle structures have only been reported from the Upper Silurian Burgsvik Sandstone Formation (Calner 2005a). Here, a wide range of wrinkle structure morphologies occur on the upper bedding plane of thick-bedded quartz arenites that show evidence for rapid deposition by currents or storm surges into deeper environments (reworked delta front sands). The wrinkle structures of the Burgsvik Sandstone occur in close stratigraphic association with a microbialite resurgence associated with the Late Ludlow Lau Event (Calner 2005a, b).

Cited references

Calner, M. 2005a. A Late Silurian extinction event and anachronistic period. Geology 33, 305-308.


Mats of cyanobacteria and other phototrophs in silicate-rich hot springs of Yellowstone Park.

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The microbial species composition of silica-depositing, mat-forming thermal springs in Yellowstone Park will be reviewed and illustrated in color. These include springs with a photoautotrophic cyanobacterium (Synechococcus) that colonizes the siliceous sinter as a biofilm up to about 72-73°C, and downstream below about 68-70°C mixes with Chloroflexus-like photoheterotrophic bacteria, forming a composite mat. The two microbes are compatible, since the cyanobacterium uses visible light, while the Chloroflexi do very well using the near infra-red wavelengths for energy (~720-> 800 nm). At somewhat lower temperatures (50-65°C), other species of cyanobacteria are added, namely Leptolyngbya (Phormidium) spp., Cyanothece sp., and others. In summer, most of these are a bright yellow to orange color with a high carotenoid content that provides high light and UV protection. Below ~45°C in most of these springs filamentous cyanobacteria (e.g. Calothrix) predominate. These produce dark-colored mats, with an abundance of scytonemin in their extracellular sheaths, a compound that shields the cells from almost all UV radiation. There is evidence (microfossil and chemical) that siliceous springs gave rise to some Proterozoic stromatolites.

In some springs the silicate content is so high that the polymerized silica impregnates upright “Conophyton”-like structures of filamentous cyanobacteria. In a few others, the siliceous sinter accumulates at a more rapid rate than can be colonized by cyanobacteria.

Acidic hot springs rich in dissolved silicates produce biofilms of Cyanidium-like eukaryotic algae (the “cyanidia”); these may sometimes reach a thickness of over 1 cm. Many siliceous deposits near the acidic springs contain striking endolithic bands of “cyanidia”.

Microbial mats associated to travertine deposits in the Baño San Ignacio mound spring, Linares, Nuevo Leon

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The Baño San Ignacio (BSI) mound spring, located in Linares, Nuevo Leon, Northeastern Mexico, represents a natural protected area that harbors not only endemic flora and fauna but also a rich microbial life represented by cyanobacteria and other diverse eubacteria in the form of discrete mats. The main biotic components, precipitated minerals and geomicrobiological interactions between microbes and minerals were identified along the substrate upon which these microbial communities develop. This work provides the first report of the inter/yearly variations of thermally moderate microbial mats and travertine in the context of the BSI geological framework. This studied area is linked to the geotectonic evolution of continental trapped waters following a closed standard circuit. One major sedimentary feature of BSI that directly links microbial life to their microenvironmental conditions are travertine, precipitated along the external facies of the basin and singular modern microbial mats developing in a few substrates of the running mineralized water from which their geochemical influence on the basin has not been addressed. This paper represents the first report of mesophiles microbial mats developing at the Quaternary sediments in BSI, a recent system with peculiar geomicrobiological characteristics. Macroscopically these mats have a clear fungal appearance and color resemble those displayed by lichens and fungal associations. However a dissecting view clearly shows that mats are composed by cyanobacteria and lamination is well-developed. In spite of the fact that Baño San Ignacio represents a classic example of a closed geochemical system where the component and ionic analysis fit well into the theoretical estimations for the composition analysis, the geomicrobiology of mats are far less common and less represented in natural environments. The identification of microbial mats was carried out by microscopic and fluorescence inspections and their relation to carbonate precipitates within the mat. Isotopes and XRD composition from travertines and waters are compared, as well as the elemental composition. Infrared spectroscopy allowed characterization of the various functional groups (R–NH2, R–COOH, R–OH). The results showed that cyanobacteria constitute a substantial part of the microbial mats developing at Baño San Ignacio, although the obvious presence of other significan bacteria remains to be investigated. Some of the calcite precipitates may occur on three distinct sites on the bacterial precipitation along filamentous populations of cyanobacteria and diatoms and therefore strongly influence the biogeochemical cycling of calcite in continental systems. A second set of experiments with fresh mats in presence of diverse minerals were carried out to investigate the physical changes in the mat texture after different processes like dehydratation, heat stress, temperature gradient exposure and irradiation for varying intervals. Microscopic visualization was used to monitor all textural changes on the mat surface. Preliminary results show that those mats incubated with minerals as halite and silica do show a preferential preservation over those mats slices incubated with clay sediments.
Mat-induced sedimentary structures in Palaeoproterozoic Gulcheru Formation, Cuddapah basin, India: Implications for tidal-flat sedimentation

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Abstract: Indigenous microbial mat-induced sedimentary structures (MISS) of subtidal origin like Old Elephant Skin, Wrinkle structure, Kinneyia ripples, Palimpsest ripples etc. are preserved within the siliciclastic basal Gulcheru Formation (~1.8 Ga old) of the Cuddapah Supergroup of the Proterozoic Cuddapah basin in the vicinity of Pullivendla town (Kottalu village), Andhra Pradesh, India. The presence of reactivation surfaces, double mud-drapes, interference ripples, ladderback ripples, flat-topped ripples, wave ripples etc. within the succession in the study area match well with the sediment accumulation in low tidal-flat depositional setting. Various types of cracks on bed-top, hitherto considered as of trace-fossil in origin, may be considered to be formed on exposed surface due to dessication or under water due to synaeresis in presence of microbial communities during Palaeoproterozoic.

Key Words: Palaeoproterozoic, Microbial mat, Kinneyia ripples, Purana, Wrinkle structure
MOLECULAR BIODIVERSITY STUDY OF CYANOBACTERIAL MATS ASSOCIATED TO THERMOMINERAL SPRINGS FROM WESTERN PLAIN OF ROMANIA

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Naturally occurring cyanobacterial mats were highly investigated in the last decades due to their resistance and productivity, especially in extreme environments, which are practically inaccessible to eukaryotic organisms. In ecological studies of microorganisms it is essential to be able to differentiate closely related organisms and because it is difficult to culture most bacteria from environmental samples, evaluation of changes in the structure of bacterial communities using only culturing methods is inadequate. A recent approach in the study of cyanobacterial communities is represented by the use of molecular techniques, this approach leading to the discovery of unique and previously unrecognized microorganisms, but the question that appears is: can molecular techniques be used independently of morphology to characterize microbial communities? Cyanobacterial mats associated to thermomineral drillings are an excellent model for studying the molecular diversity and the colonizing potential of cyanobacteria because they have precise spatial delimitation and homogenous conditions enforced by constant temperature and water chemistry. Our research was mainly based on culture-independent molecular analysis of cyanobacterial ribosomal *rrn* operon (16S RNA and ITS - Internal Transcribed Spacer). PCR amplification of target fragments with cyanobacterial primers from genomic DNA extracted from field samples was followed by: 1. cloning, restriction map analysis and sequencing of selected amplicons; 2. capillary electrophoresis of PCR amplification products (ITS); 3. Denaturing Gradient Gel Electrophoresis (DGGE) banding patterns analysis and sequencing of selected gel DNA fragments. The conserved fragments of 16S rRNA gene and ITS were used for taxa identification and genotype heterogeneity analysis; a phylogenetic analysis was also conducted. The use of molecular techniques for biodiversity investigation of cyanobacterial mats associated to thermal springs found in Western Plain of Romania has proved to be successful. They provided all the necessary aspects for estimating the number of species from the community (using capillary electrophoresis and DGGE), for species delimitation (using restriction map analysis) and species identification (BLAST analysis of the rDNA-ITS sequences). The comparison of the sequences we obtained with those stored in public nucleotide databases revealed that the majority of taxa belong to the following genera: *Phormidium*, *Symploca*, *Oscillatoria* and *Microcoleus*. 
Preservation of recent footprints in an estuarine tidal-flat with development of microbial mats: implications for the analysis of fossil tracks

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Field studies in a mesotidal flat in Bahia Blanca estuary, Argentina, reveal the presence of extensive areas with microbial mats, covering the upper-intertidal and lower-supratidal areas. Studies of recent environments with microbial mats increased considerably during the last years, not only because their unique sedimentologic and ecologic characteristics, but also because they provide important implications for the understanding of fossil environments and paleocommunities. The main purpose of this research was to evaluate the role of microbial mats in the preservation of biogenic structures. We recorded the distribution of recent traces all over the tidal-flat, although focused the analysis on the preservation of large bird tracks. Several footprints were selected and photographed, recording the morphological modifications they experienced during four months. During this time, most of the footprints showed resistance to tide- and wind-erosion, and also to heavy rains and storms that affected the tidal-flat. This resistance was clearly associated to the presence of the microbial mats, which are known to biostabilize the sediment. Also, microscopic analysis of the tidal-flat sediment revealed the presence of zeolites and calcite, suggesting early cementation, which may have favored the consolidation of the footprints. Mat-thickness also affected the morphology of the footprints; in areas with thick microbial mats overlying soupy sands, the tracks were deeply impressed and did not show fine details. On the contrary, in zones with thin microbial mats overlying relatively stiff muds, the traces were shallow and preserved details such as skin impressions and skid-marks. Also, both types of footprints were affected by mat growth, although in the shallow traces the modification was faster, and the fine details were progressively obliterated. This study yields valuable insights into the relationship between microbial mats and morphology of the footprints, and provides key information for the analysis of fossil tracks in equivalent paleoenvironments.
Microbes have been recognized for their ability to decompose organic matter almost as long as the recognition of microbes themselves. Though it has only been in the last few decades that microbes have begun to be recognized for their potential to preserve tissues as well. Even though some suggested that microbes could play such a role at least as early as 1864, it remained only a hypothesis for almost 120 years. Work done by Allison and others in the eighties opened the door to experimental research suggesting that microbes not only aid in fossilization of soft tissue, but may even be required. The nineties saw an explosion of work that provided strong evidence that the role of microbial mats in both maintaining carcass integrity and quickly mineralizing tissues key to exceptional fossilization—even in conditions not amenable to inorganic precipitation. Recent work has now shown that bacteria and possibly even fungi may be important for “normal” fossilization of bone as well. Further work continues to expand our understanding of the role microbes play in preserving ancient life as fossils.
Microbial Mats in Modern Environments: Portals to Understanding Precipitation

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Microbial mats exhibit dense horizontal arrays of different functional groups of bacteria. In open-water marine stromatolites at Highborne Cay (Bahamas), cyanobacteria, sulfate-reducers, aerobic heterotrophs, and sulfur oxidizers interact during the tripartite cycling of surface mats that result in precipitation of micritic laminae composed of CaCO₃. Activities of sulfate reducing bacteria (SRB) have been closely related to precipitation events occurring within surface mats of stromatolites. Studies indicate that surface mats exist as different states along a continuum between a non-calcifying (Type 1) to a calcifying (Type 2) state. Fluorescence in-situ hybridization (FISH), using 16S rRNA oligoprobes (SRB385 and dsrAB), is used to target important microbial groups such as SRB, and when coupled with confocal scanning laser microscopy (CSLM), can be used to examine changes in the in-situ microspatial organization of mats that occur across this continuum. Results show that many mat bacteria show microspatial aggregations of different sizes, resulting in clusters within clusters. The progressive organization in microspatial distributions (i.e. clustering) of SRB and other bacteria is now associated with bacterial chemical communication, called quorum sensing (QS). QS potentially allows many individual bacteria to coordinate activities as a group. It will be discussed whether the precipitation of micritic laminae (i.e. horizontal layers of CaCO₃), which is a characteristic feature of fossil and present-day marine stromatolites, may be influenced by such processes.
Modern microbially-induced sedimentary structures in a peritidal environment – northern Kuwait

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Microbially-induced sedimentary structures, including siliciclastic oncolites, have been discovered in coastal aeolian sands in northern Kuwait. The area lies south of the depositional basin of the Tigris-Euphrates estuary. The microbial structures occur with physical sedimentary features that indicate drowning conditions of a continental nebkha facies. These observations support the interpretation of a peritidal setting for the microbial structures within tidal-dominated flooding across a shallow ramp. The siliciclastic oncolites are forming in a shallow sub-tidal to intertidal environment with excessive hydraulic energy, where periods of high wave erosion are interrupted by periods of low sedimentation. Multidirectional ripple marks document a series of erosion events interfering with microbial stabilization in lower supratidal settings. Polygonal and prism shrinkage cracks form in channels isolated in supratidal environments and cover cyclic sedimentation of algal mats. The plethora of new observations include, pseudo-microbial salt-encrusted crinkle structures, bioturbation activity, an array of almond-shaped oncolites encrusted in autochthonous sand and shell fragments (and many other detritus), rip-up algal mat deposits, and ephemeral textures. These associations of the microbial colonies with the high-energy siliciclastic erosion rates support earlier models of microbial activity in high stress sedimentary environments, and extends the possibility in the geological record of newly-interpreted microbially-induced sedimentary structures.
Paleoenvironments Recorded by Earth’s Earliest Terrigenous Sedimentary Rocks: Evidence from the Barberton Greenstone Belt, South Africa and the Jack Hills Belt, Australia.

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Archean terrigenous sedimentary rocks preserve a record of Earth’s earliest terrestrial through marine depositional settings. Shallow-marine deposits provide evidence for tides and preserve early evidence of life. The Moodies and Fig Tree Groups in the Barberton Greenstone Belt and the Jack Hills succession in the northwest Yilgarn Block of Australia range in age from 3.0 – 3.3 Ga and consist predominantly of terrigenous sedimentary rocks. Sediment compositions are dominated by plutonic quartz and provide evidence for the first emergence of continental land masses starting at ca. 3.3 Ga. The Fig Tree Group consists of turbidite beds of different type that indicate deposition mainly below storm wave base. Rare hummocky cross beds imply periodic shoaling of the depositional interface to storm wave base. Alluvial facies dominate the Moodies Group that also contains subordinate shallow-marine facies. The Jack Hills Belt, the site of discovery of the oldest zircons on Earth, consists predominantly of terrigenous sedimentary rocks. Progradational alluvial fan/fan delta facies are capped by a transgressive unit of well-sorted quartz arenite-gritstone of probable tidal origin.

Shallow-marine deposits preserved in the Moodies Group provide important constraints on the nature of physical processes in the early ocean. Quantitative evidence for tides is preserved in a tidal sand-wave deposit as bundles of sandstone foresets separated by mudstone drapes. Detailed analysis of rhythmic foreset bundle thicknesses reveals a hierarchy of diurnal, fortnightly, and monthly tidal periodicities. Tidal structures in the Moodies Group imply not only the presence of the Moon at 3.2 Ga but also are suggestive of normal tidal amplitudes and moderate tidal current velocities. Tidal cyclicity recognized in the sand-wave deposit is comparable to that recorded in modern tidal settings and is compatible with a lunar orbital shape similar to that existing today. Stacked upward-finining, decimeter- to meter-scale cycles are attributed to alternating subaerial exposure and fluvial influx followed by marine inundation probably related to absolute sea level fluctuations. Evidence for tides is preserved as cross beds with mudstone drapes, and interlaminated sandstone-siltstone and mudstone. Abundant exposure structures in interlaminated sandstone-siltstone and mudstone indicate that the cycles are upward shoaling. Tidal flat facies consist of planar-laminated, cross-stratified and wave-rippled sandstones with abundant desiccated mudstone drapes. Desiccation cracks vary in scale and degree of complexity and desiccated surfaces contain abundant wrinkle structures.

Inferred biosignatures of ancient microbial mats are preserved in tidal sandstones of the Moodies Group and differ fundamentally in appearance and genesis from Early Archean stromatolites and bacterial fossil remains preserved in chert. Wrinkle structures, desiccation cracks, and roll-up structures record microbial mats enriched in extracellular polymeric substances that effectively stabilized sediment of the earliest known siliciclastic tidal flats. The biogenicity of these sedimentary structures is supported by the presence of identical biosignatures from similar tidal habitats throughout Earth history and suggests that siliciclastic tidal flat (as well as eolian settings) have been the habitat for thriving microbial ecosystems for at least 3.2 billion years.
Seven unique distinctly different morphotypes of concretions are present in regolith at two small sites at the base of the Meski Plateau near Erfoud, Morocco. Morphotypes are elongate, spheroidal, banded, botryoidal, columnar, rosette, and speleothem. The concretions formed in the Neogene from much older porous sandstones. Most concretions are isolated hand samples, but some are meter-sized blocks of coalesced concretions; not one example resembles any surrounding outcrop or bedrock in terms of morphology. The barite rosettes formed first as regolith and concretion nuclei, by mixing of $\text{Ba}^{2+}/\text{SO}_4^{2-}$ saturated sub-surface solutions. The speleothem formed in a large void within the porous sandstone. The sand concretions formed when calcite precipitated around sand grains in unconsolidated quartz sands with cyclic fluctuation of $\text{Ca}^{2+}/\text{CO}_3^{2-}$ saturated ground water. Petrographic analyses, stable isotope data, morphology, and scanning electron microscopy indicate that microbial processes induced initial cement precipitation, producing the concretions.


Signatures of microbial mats in metalliferous Kupferschiefer deposits (Upper Permian, Zechstein) of SW Poland

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Permian Kupferschiefer beds of SW Poland contain laminae rich in organics and metal. Microstructures include variably thick laminae of even, wavy, or lenticular shape. Duplets of light laminae (20 µm to 1 mm thick) including fine crystalline dolomicrite, locally also calcite mixed with clay, and dark ones containing clay and organic matter, partly mixed with micritic carbonate are frequent. Lenses of detrital quartz (rarely feldspar and muscovite) interrupt the laminations. Lamina contacts to carbonate or clayey layers are partly indistinct. The proximal facies contains 2-7% TOC, whereas distal organic laminae include 5-7% TOC. Matrices of clay and amorphous organic matter contain sediment grains and minerals within pore spaces. The latter comprise fine-grained framboidal pyrite, euhedral galena aggregates, locally illite, kaolinite and chlorite. SEM of the organic layers reveals a morphologically diverse microfossil record including filamentous and spheroidal structures, the latter pointing to former unicellular colonies. Hollow cylindrical microstructures suggest leftovers of sheath-enclosed filaments. Amorphous dark chips may be remains of EPS-enriched bacterial biofilms. These are rich in metals and aluminosilicates. Kupferschiefer laminations are commonly interpreted as products of periodic supply of organic and non-organic material. Alternations of lighter and darker laminae reflect seasonal variations in planktonic and benthic production. Although there is no macroscopic evidence, the microstructures imply rapidly decaying microbial mats. Organic-rich laminae are interpreted as remains of benthic microbial mats, whereas the light gray laminae may indicate episodes of stronger sedimentation. Episodes of stagnant sedimentation may have favored microbial mat growth. The paleoenvironment implies a low energy shelf bottom. Preserved microbial laminations hint to metal enrichment during early diagenesis rather than post-depositional mineralization. Decaying stacks of biofilms may have induced bacterial sulphate reduction and Fe-sulphide formation in pore water enriched with reactive Fe.
Biogenic fabrics in metalliferous Weissliegendes deposits (Upper Permian, Zechstein) of SW Poland

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The upper Weissliegendes (Zechstein Sandstone), underlying the Kupferschiefer and/or Zechstein Limestone (Ca1) units of SW Poland, is usually up to several (max. up to 40 m) thick, consists of cross-bedded quartz arenites cemented mainly by calcite and anhydrite. It contains marine fauna, is of low organic carbon (<0.4%) and bioturbated at the top. The sandstones record the beginning of the Zechstein transgression and have been deposited in shallow marine, probably wave-dominated environment.

The upper part of the Zechstein Sandstone contains copper-polymetallic minerals up to economic values. In general the copper sulfide minerals comprise intervals from a few cm up to 20 m and downwards become less intensive and finally disappear. The sulfides fill interstitial space forming more or less massive or disseminated cements (up to 30 µm in size). It occurs as organic-enriched concretions and bands. (very light sulfur [published: δ34S from -39 to -44‰]). Characteristic features of the Zechstein Sandstone in the mining area of SW Poland are thin (0.5 to 2 cm thick) copper sulfide bands below the Kupferschiefer. The laminated intervals (several tens of the bands) are up to 2 m thick and continue through a few tens of meters of distance at least. The bands are slightly inclined and often discordant to bedding. They are usually spaced (0.5-2 cm), have generally a sharp base and diffusive upper boundary. The streaks of the lowest as well as the uppermost units are less distinct. The bands contain mainly copper sulfides (digenit and chalcocite), rarely other sulfides. SEM studies reveal filamentous and coccoidal microfossils often enriched in Cu and Fe (EDX). Present are also mucoidal organic matter and honey-comb structures.

Recently a post-sedimentary replacement of copper mineralization has been assumed mainly because of the lack of primary sources of H2S and due to metal impregnation and replacement of feldspar, quartz and lithic grains by sulfides. In this context the sulfide bands may have been formed by interaction of biogenic H2S diffusion from the overlying Kupferschiefer (from early steps of bacterial sulfate reduction in the shale) into the sandstone (Weissliegendes) and simultaneous dissolved metal migration from below. However, the characteristic features of the bands (sulfide mineralization, sharp lower boundary, concentration of sulfides at the base of the bands and their dissemination upwards, presence of microbial structures) suggest synsedimentary formation of at least part of the metal sulfides.
The role of microbial mats and organic matter in early diagenesis of Ediacaran siliciclastic sediment.

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Abstract: The preservation of impressions of large soft-bodied organisms in sand-sized sediment is a phenomenon that is restricted largely to the Ediacaran. This has led to proposals that organisms of the Ediacara biota were constructed of particularly tough biological materials not found in living groups of animals. However, studies of well-preserved Precambrian sedimentary sequences, from the Archean to the Ediacaran, show that evidence of microbial mats and films was just as common in siliciclastic sediment as in chemical sediment. A model for the preservation of features attributed to microbial mats also applies to larger biological objects.

Megafossils of the Ediacara biota, preserved as casts and molds, are products of early diagenesis mediated by association with rich organic detritus and microbial films both on bedding surfaces and as large organic masses within massive sandstone beds. In the quest to document the diversity of the Ediacara biota, most previous studies have isolated geometrically regular fossils at the expense of the “biological noise” preserved on the same fossil-bearing surfaces. The recognition of microbially induced sedimentary structures (MISS), and textured organic surfaces (TOS), has drawn attention to the presence of the rich organic contribution to Precambrian communities in the form of biofilms, dense organic mats and matted communities of benthic organisms associated with individual bodies of better known members of the Ediacara biota. Attachment discs and polypoid animals were preserved below mats as composite casts, while epibenthic organisms living above mats were preserved as external molds. Benthic organisms and mat shards, ripped-up by storm events from benthic communities near fair-weather wave-base, were transported offshore by sand flows into deeper settings.

Sand smothering of any bed surface coated with organic matter could lead to bacterially induced pyritization of the sole veneer of the overlying bed, as a “death mask” of the entire substrate, provided that the upper surface of the bed was rapidly sealed to limit oxidation of the buried remains. Likewise, transported bodies and mat shards could be molded within massive, grain-flow sandstones. The discovery of fossils within outcrops of massive beds depends on fractures that follow the partings left by sand-filled or collapsed bodies within these beds. Fossiliferous bed partings and fossil partings, typically limonitic in weathered outcrops, were originally pyritic in most cases.

The base of the Cambrian, defined by the earliest penetrative burrows and small shelly fossils represents a leap from two-dimensional ecology, which was at its zenith in the Ediacaran, to three-dimensional ecology embodied by the “Cambrian explosion”. The advent of seafloor burrowing and predatory interactions not only prompted an arms race in marine ecology but also, like
grave robbing, progressively reduced the possibility of preserving soft-bodied organisms in well-aerated Phanerozoic seafloor sediment.

In the absence of penetrative burrowing, during times of high biological productivity in Precambrian aggradational sedimentary settings, microbial sealing may have led to considerably greater trapping of organic matter than in equivalent Phanerozoic strata. Furthermore, microbial mats would have greatly increased the preservation potential of Proterozoic sandstones perhaps accounting for the dominance of these deposits in the Neoproterozoic-Cambrian record. Considering the sheer density of body fossils and microbial mat communities in some Ediacaran lagerstätten, the Ediacaran is likely to have been a time of major hydrocarbon accumulation as evidenced by recent discoveries in the Arabian Peninsula, Siberia and China. While often attributed to stromatolitic facies, microbially layered siliciclastic sediments should not be overlooked as both source and reservoir rocks for Precambrian oil.
Experimental microbial sedimentology: Producing primary structures in sand

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Interpreting the physical dynamics of ancient environments requires understanding how primary structures such as ripples, dunes and plane lamination are created. Traditional interpretations of these structures are based on experimental flume studies of unconsolidated quartz sand, in which stepwise increases in flow velocity produce a succession of sedimentary structures comparable to those found in the rock record. Yet cyanobacteria, which were excluded from these studies, are pervasive in wet sandy environments and secrete sufficient EPS to inhibit grain movement, to increase the flow velocities under which sedimentary structures form, and to form new types of bedforms.

Flume experiments using microbe-inoculated quartz sand demonstrate that bacteria strongly influence the behavior of unconsolidated sand. In freshly inoculated but unbound sediment, ripple production is retarded by nearly 50% compared to the same experiment conducted in sterile sand. Moreover, in weakly developed biofilms, ‘no grain movement’ occurs at flow velocities under which ripples would normally form in sterile sand. Flip-over and rip-up structures form before ripples are produced, and ripples occur only when flow velocities are more than twice as high than would be required in sterile sand. Thus, even the thinnest microbial films can more than double the flow velocity required to produce the traditional sequence of ripple→dune→plane-bed-lamination bedforms and can inhibit the growth of ripples or dunes entirely. Thicker microbial mats cause ‘terracing’ of erosional edges, they foster transport of multi-grain aggregates, and they yield a bedform progression consisting of flip-overs→roll-ups→rip-ups of bound sand. After this bedform progression, the bed then passes directly into the dune phase without passing through production of ripples.

Roll-ups, rip-ups, and flip-overs are common in ancient microbially dominated environments and ripples, dunes, and plane-bed lamination are common in nearly all sandy aquatic environments. The production of these structures is strongly influenced by coccoidal and filamentous bacteria – both today and in the past.
Microbial mats in Lower Triassic siliciclastic playa environment (Middle Buntsandstein, North Sea)

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The Lower Triassic siliciclastic sequence of the Germanic Basin is predominantly composed of terrestrial deposits under semiarid to arid climatic conditions. In the Lower Buntsandstein unit, (non-?)marine stromatolites and oolites occur in the central part of the basin (cf. Kalkowsky, 1908). Here we first describe the formation of microbial mats in the Middle Buntsandstein unit (Helgoland Island, Central North Sea) which is interpreted as a playa-related environment. Microbial mats are intercalated in a depositional sequence of reddish silt- to fine-grained sandstones. Besides even lamination internal sedimentary fabric is dominated by desiccation cracks, dewatering structures, internal brecciation, mm-sized graded layers, and small-scale oscillation ripples. Additionally, some distinct sandstone beds of eolian origin occur. Calcareous units of variable thickness (mm to several cm) contain signatures of microbial mats, e.g. internal fine lamination. Several laminae show a wavy-crinkly character well known of modern biolaminites. Various laminae indicate internal spongy fenestrate fabrics comparable to fabrics produced by modern mats dominated by photoautotrophism. In modern mats fenestral fabrics often are related to the pressure of gas released from decaying organic matter. Also oscillation ripples coated by biolaminae indicate photoautotrophism. Finally the bedding planes show a number of features known from modern microbial mat habitats in sabkha or playa environments, among others elongated bulges related to polygons, and domal build-ups. In addition, heterogeneously shaped fragments showing fine laminations may be interpreted as chips released from the mats. Prolific microbial mat growth is known from a variety of ancient and modern sabkha and playa environments. In such settings, a wealth of sedimentary structures develops from active growth responses of mat-forming microbes to disturbances by the external environment.
Microbial mats and stromatolites in the Late Ordovician Eureka Quartzite

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The late Ordovician Eureka quartzite in the Great Basin consists predominately well-sorted quartz arenite with abundant planar, trough, and herringbone cross stratifications indicating high-energy depositional environments. In such environments, microbial mats and stromatolites are not expected due to the instability of sandy substrates that could be easily modified by waves and tides. Surprisingly, well-preserved domal stromatolites up to 2 m wide and 1.5 m high are found in some intervals that contain more than 70 vol. % quartz grains and abundant cross stratifications clearly indicating intensive wave and tidal activities. In contrast, laterally continuous microbial mats are present mostly in finer-grained sandstone and siltstone with parallel laminations indicating less agitated environments. The presence of stromatolites in cross-bedded sandstone indicates strong biostabilization of microbial mats effectively prevented erosion during storm events, and the prevalence of translucent quartz sand grains permitted light penetration into the sediment, leading to thick microbial mat accretion and the formation of domal stromatolites. Instead, the abundance of microbial mats in relatively low-energy environments suggests slower sediment accretion favorable for microbial mats to expand laterally. In high-energy depositional environments, large-scale stromatolite domes and clusters could have served as localized shelter for further microbial mat colonization, forming patchy stromatolite and microbial mats. Enrichment of iron minerals including pyrite and hematite within dark internal laminae of the stromatolites suggests that mat-generated organic matter was mineralized under locally anaerobic conditions. Anaerobic mat mineralization may have created elevated carbonate alkalinity in pore spaces of sandy sediment, promoting early cementation/lithification of microbial mats and stromatolites. The occurrence of stromatolites in the Eureka Quartzite provides an example of microbial growth in highly stressed siliciclastic sedimentary environments and provides insights into the development and preservation of microbial structures in siliciclastic settings.
Microbial mat-related structures in Quaternary Mn-oxide and barite deposit, Cape Vani, Milos, Greece

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Abstract

Evidence is provided for the existence of microbially induced sedimentary structures (MISS) in Lower Pleistocene siliciclastic sediments that host the Vani Mn-Ba deposit, NW Milos Island, Greece. Milos island is a recently emergent 2 Ma volcano of the Pliocene—modern South Aegean volcanic arc. The deposit occurs in a 1 km long marine rift basin floored by a dacite dome. Basin fill is a 35-50 m thick sequence of glauconitic sediments sandwiched between volcaniclastic sandy tuffs/sandstones. The occurrence of dacite intrusion, and glauconitic sediments which are cut by barite-silica feeder veins and host white smoker structures, suggests rift-induced sudden deepening from shallow high-energy sandy sediments, and shallow-marine hydrothermal venting. This was followed by rapid uplift and near-shore littoral sedimentation and hydrothermal venting and subaerial emergence, manifested by: (1) deposition of inferred transgressive sandy tuffs (i.e. herringbone cross-beds, ripples, slumps, bioturbation), (2) barite-silica veins, and, (3) overlying gravel and cracked silicified mudstone. We have recognized MISS structures in the uppermost sandy tuffs which include leveled depositional surfaces and wrinkle structures affected by grazing and bioturbation, curled crack margins, erosional remnants, gas domes, thrombolitic fabrics, cracking and upturning of crack margins, sponge pore fabrics, and mat slump structures. The host siliciclastics consist of plagioclase, K-feldspar, biotite, glass shards, clay and silica clasts, overprinted by a silica—K-feldspar—illite—barite assemblage. Most of these features contain authigenic Mn oxide minerals, developed interstitially among the clasts and secondary minerals. Mn—oxides may consist of X-ray-amorphous hollandite— and romanechite—like minerals, δ-MnO₂—like phases and poorly-crystalline todorokite. The presence of Mn-mineralized MISS may suggest the possible role of cyanobacterial photosynthesis in Mn²⁺ biooxidation and Mn-oxide biomineralization.
Degradation spectra of Early Silurian coccoid cyanobacterial mats: Significance for identifying traces of oldest life

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The intensity and mode of post mortem degradation processes of organic matter depends on an interplay of geological and biological factors which dictate the final appearance of fossilized remains of organisms. Analysis of an array of preservation spectra of benthic coccoid cyanobacterial mats in marine Early Silurian black cherts and siliceous shales from the Sudetes Mts., (southwestern Poland) provides a quantifiable example of this process. These samples represent each of the degradation stages of cyanobacterial mats in cherty- and shaley-media that range from morphologically well-preserved structures, to almost totally degraded amorphous organic matter. The gradational nature of the degradation process documented in the studied mats offers important clues for the identification of many ancient problematical carbonaceous microfossils, particularly those from Archean rocks.

Two basic modes of degradational process are recognized in the studied mats: (i) early post mortem biodegradation; and (ii) late diagenetic thermal degradation. The latter process led to partial transformation of the fossilized organic remnants of cyanobacterial mats (sheaths and capsules). Thermal degradation resulted in the formation of objects morphologically distant from the original microbiota; however features remain that yet allow for their identification as bona fide biogenic structures. Furthermore, our observations show that some of the thermally-generated Silurian “neofossils” are strikingly similar to the controversial microfossil structures described from black cherts of the Paleoarchean Apex Basalt of Western Australia. These observations open a promising means for credible recognition of remnants of cyanobacteria in thermally metamorphosed Archean sedimentary rocks.
Microbial biofilms and the preservation of the Ediacara biota

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ABSTRACT

The terminal Neoproterozoic Ediacaran period is typified by the Ediacara biota (ca 579-542 Ma), which includes the first morphologically-complex macroscopic organisms. Both the taphonomic setting that promoted the preservation of the soft-bodied Ediacara biota in coarse-grained sediments, and the influence of associated microbial coatings on this process, have generated much debate. Specimens of Ediacaran discs (Aspidella) from the Fermeuse Formation of Newfoundland, Canada, were analyzed using environmental scanning electron microscopy (ESEM) to determine the relationship between the fossil specimens and the surrounding sediment. The presence of chemically distinct finer-grained sediment surrounding the upper and lower margins of the Ediacaran fossils is consistent with elemental analyses of well preserved bacterial biofilms from other localities. Ediacaran discs were likely entombed within a bacterial extracellular polymeric substance (or exopolysaccharide, EPS) during life, which added structural stability to these frond holdfasts, and facilitated their subsequent fossilization. Microbially-mediated preservation in Fermeuse-type Ediacaran taphonomy provides an explanation for the dominance of Aspidella holdfasts in these settings, and suggests that the overwhelming dominance of circular to bulbous forms such as Aspidella in Ediacaran biotas around the world is a direct result of the interplay between microbial ecology and microbially-mediated taphonomy.
MORPHOLOGY AND COMPOSITION IN TROPICAL INTERTIDAL AND SUPRATIDAL MICROBIAL MATS, MOOREA, FRENCH POLYNESIA

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Microbial mats covering a tidally-inundated mudflat on Moorea, French Polynesia show seven morphologic mat types, correlated broadly with tidal levels. In order to test this classification and to characterize and describe the mats, 33 mats encompassing all seven types were examined using light microscopy. The mats were dominated by cyanobacteria belonging to the genera Lyngbya and Microcoleus. Other cyanobacteria genera including Oscillatoria, Phormidium, Xenococcus, and Chroococcus as well as unidentified cyanobacteria and diatoms were also present. Species dominance and frequencies differed between the pre-defined types. All mats were vertically stratified, although to different degrees, and thickness ranged from 1mm to 30 mm. Although the number of laminations differed, most mats had an upper green gelatinous layer and a lower reddish layer. A PCA analysis comparing the environmental and compositional data for 27 mats challenged the pre-defined categories, suggesting that the mats are better grouped into four categories. These results along with a cluster analysis and findings in the literature indicate the presence of two primary types: a reticulate/smooth mat and a blister mat, as well as two types along the periphery of these in various stages of lithification. Extensive extracellular polymer production was present in all mat types, and allowed the mats to bind sediment. Grazing and bioturbation was present in most mat types, and consisted primarily of nematodes and amphipods. Average salinity of the groundwater was 6.8% and temperatures ranged from 28-48 °C, indicating an extreme hypersaline environment similar to those characterized for microbial mats in other tropical regions.
Kinneyia Microbial Mat Structures from the Cenomanian (Cretaceous) of West Texas.

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Kinneyia (Walcott, 1914) microbial mats are generally interpreted to be cyanobacterial in origin, and have been described primarily from Proterozoic siliciclastic sediments, with less common examples through Jurassic in age. The occurrence in the Del Rio Formation in West Texas extends this stratigraphic range. Kinneyia, commonly referred to as “wrinkle structures, characterized by millimeter-scale flat-topped, winding ridges and intervening troughs and pits” (Porada and Bouougri, 2007), is normally found on top surfaces of sandstone beds.

While many authors interpret Kinneyia to have formed in intertidal to shallow subtidal zones, consistent with cyanobacterial activity, there is also a commonly reported association with tempestite deposits, possibly from somewhat deeper water settings. This is the case with the Cretaceous Del Rio Formation of West Texas, which consists of calcareous shales and argillaceous limestones with scattered siliciclastic sands, lacking any signs of tidal energy.

The Del Rio Formation (Cenomanian) is well exposed in outcrops along U.S. Highway 90 in Val Verde and Terrell counties of West Texas, and again in exposures in Brewster County. In several localities close to Comstock (Val Verde County), in the Black Gap Wildlife Management Area (Brewster County) and near Terlingua (also Brewster County), Kinneyia occurs on top surfaces of siliciclastic tempestite sands. The tempestite interpretation is based on several features: tool marks on basal surfaces, gutter casts, graded bedding, and hummocky cross stratification in particular. Invertebrate paleontology (dominance by oysters and agglutinating foraminiferans) and trace fossils suggest a mid-shelf setting with fluctuating salinities, consistent with frequent tropical storms. A recurring question concerns the nature of the inferred temporary hostile conditions prevailing immediately after introduction of the tempestite sands, which permitted the preservation and burial of the mat before grazing organisms had the opportunity to destroy the microbes. Similar microbial mats are rare in the Phanerozoic, and it is likely that this can be attributed to grazing invertebrates. Possible explanations include disturbance of anoxic sea-floor sediments by the storm surge relaxation currents, creating a temporary lack of the oxygen needed by grazers.

The Del Rio occurrences of Kinneyia extend its stratigraphic range by approximately one hundred million years, and are significant for that reason alone. The well established relationship with tempestite sediments is also notable.
Microbially induced sedimentary structures in the Lower Old Red Sandstone, South Wales, UK: indicators of an early terrestrial trophic structure?

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Apart from reports of freshwater stromatolites in the Orcadian Basin, microbially induced sedimentary structures are not well known from the Lower Old Red Sandstone of the British Isles. A variety of enigmatic sedimentary structures and markings that are attributed to the activity of cyanobacteria have been observed in the late Silurian and early Devonian terrestrial rocks of South Wales. These are millimetre ripples, wrinkle marks, ‘cauliflower’ and ‘molehill’ structures, calcretized matgrounds, ‘pepperpot’ and ‘fairy ring’ structures. Most of the structures occur on very fine- to fine-grained sandstone bedding surfaces or, as in the case of the ‘cauliflower’ and ‘molehill’ structures, on bedding surfaces of tuff beds. Most of the millimetre ripples and wrinkle marks occur in both inclined and non-inclined red heterolithic deposits that form a large part of the Pridolian and Lochkovian succession of the Lower ORS in South Wales. These deposits consist of conspicuous units up to 3 m thick, comprising millimetre- to centimetre-scale lamina sets of alternating mudstone and fine-grained sandstone that have been interpreted as deposits of muddy point bars or accretionary benches on ephemeral channel margins or as crevasse-splay lobes or distal flood-out deposits from ephemeral flow. These deposits are also rich in trace fossils reflecting animal locomotion, burrowing, foraging, ploughing and resting. Wrinkle marks and millimetre ripples are related to rapid growth of cyanobacterial mats on fresh, wet muddy-bar and channel surfaces, especially in films of standing water, and may have been a critical basal constituent of the food chain for terrestrial communities. The pustular ‘cauliflower’ and ‘molehill’ structures preserved on the tuff beds have been linked to algal blooms that followed an increase in nutrients after deposition of the ash into shallow floodplain ponds. The tuff beds are also associated with a diverse ichnofauna and it is likely that opportunistic colonizers moved in to take advantage of the abundant food source. Preservation of the delicate trace fossils in the Lower ORS in the tuff beds and on the muddy bars was probably aided by the mat grounds that provided a bio-glue to hold fine sediment together.
Microbially-induced sandcracks in a Tonian siliciclastic foreshore setting (Rehoboth, Namibia).

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In the Rehoboth District of Namibia, weakly deformed early Neoproterozoic (Tonian) sedimentary rocks of the Doornpoort Formation form the base of the Tsumis Group, Sinclair Supergroup. These rocks form a 4500m-thick succession of red feldspathic quartzites, with very few thin interbedded red shales, overlying an impersistent basal conglomerate with pebbles and boulders of underlying Mesoproterozoic igneous basement rocks. The quartzites are characterized by the presence of planar crossbedding, with thin lenticular intercalations of conglomerates containing basement clasts, which are more common in the lower part of the succession, which was regarded as having been deposited in braided river environments.

Our recent mapping on the farm Eindpaal 518 indicates that these sedimentary rocks were deposited in a marginal marine mesotidal foreshore environment. Sedimentary structures commonly found include ripple marks, swash marks, and dm to m-thick planar crossbed sets. The ripples include flat-topped ripples, indicative of emergence and slack-water modification, and standing-wave “tadpole-nest” ripples produced by interference of two arcuate wave trains.

Within this siliciclastic succession, a solitary bed containing “sandcracks” was discovered. It contains a prominent polygonal network of raised ridges (1-2 mm high), with the polygon sides being about 1 to 2 cm. The polygonal network covers the entire exposed bedding plane (~30 cm by 5 m ) of a quartzite, with no shale present. The polygons are not regular, but appear flattened, parallel to the axial plane of regional folds. This “sandcracked” bed is interpreted to have resulted from the exposure and desiccation of a thin algal mat, a few mm thick, formed on a sandy siliciclastic substrate, which was then covered by more sand, which infilled a shallow polygonal network of desiccation cracks. The algal mat subsequently decayed after burial, leaving just the sandy infill of the crack network as a palimpsest of its former presence.
Facies control on wrinkle structure development: Examples from the Lower Cambrian and Lower Triassic

Scott A. Mata* and David J. Bottjer

The distribution of microbially mediated sedimentary structures has long been known to have temporal variability, with most subtidal microbial mat-related structures falling from prominence at the Precambrian-Phanerozoic transition and being restricted to stressed, marginal marine settings during the post-Cambrian Phanerozoic. This distribution is commonly regarded a guiding principle in paleoenvironmental analysis, yet it is now well documented that during intervals of environmental stress, such as during intervals following mass extinctions, microbial mat-related structures make a resurgence into open marine environments and occupy depositional environments that would otherwise be dominated by pervasive bioturbation under normal marine conditions, thus restricting mat development.

During intervals such as the Early Cambrian and following mass extinctions events, when bioturbation is known to be low, microbial mats do indeed occupy normal marine environments beyond stressed marginal marine settings. In the absence of pervasive bioturbation, microbial mat-related structures should be limited only by physicochemical parameters, and yet features such as wrinkle structures appear to show a strong facies dependence.

Wrinkle structures from the Lower Cambrian and Lower Triassic share many similarities in terms of depositional environment and preservation mode. During each interval microbial features are typically cast on an underlying sandstone and are preserved by finer-grained siltstone or shale. Common wrinkle structure-bearing facies include interbedded siltstone and hummocky cross-stratified sandstone, interpreted as being deposited between fair-weather wave base and storm wave base, and flaser and lenticular bedded sandstone and siltstone of a tidal flat environment. This commonality between very disparate time intervals suggests a conservation of processes that lead to the development of wrinkle structures and possibly other microbial mat-related structures.
The interaction between Proterozoic atmosphere, lithosphere and biosphere; aeolian systems in Singhbhum Crustal Province, eastern India

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This study is focused on aeolian facies associations in the Palaeoproterozoic Dhalbhum Formation and the Mesoproterozoic Chaibasa Formation outcropsing in Singhbhum Crustal Province (Bihar (now Jharkhand) and Mayurbhanj Districts). Field observations, grain-size analyses in thin sections, and SEM observations show similarities and differences between the different aeolian facies associations in the Paleo-mesoproterozoic.

Aeolian dune deposits in the Paleoproterozoic Dhalbhum Formation show several metres-thick cross-bedded intervals. Dune deposits are mainly quartzitic and display very good sorting and rounded grains, slightly deformed during metamorphism. Locally, aeolian deposits display a bimodal grain-size distribution and pin-stripe lamination, visible in outcrop and thin sections.

The Mesoproterozoic Chandil Formation displays aeolian sand-sheet facies associations of superimposed tabular strata consisting of wind-ripple lamination. Wrinkle structures separate aeolian-sand-sheet deposits. The wrinkle structures occur over extensive surfaces, and may be associated with organism-sediment interaction. The quartzites of the Chandil Formation match the mean size of aeolian deposits in desert aeolian dunes (2-3 Φ). The interaction between synsedimentary tectonics and the groundwater table led to the preservation of the aeolian deposits.
Secular changes in seawater trace metal chemistry recorded in sulfides preserved in Precambrian banded iron-formations and stromatolites

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We report data that indicate secular changes over geologic timescales in biologically-important trace metal concentrations (Ni, Co, Cr, Cu, Zn, Mo, Mg, Mn) as recorded in sulfide phases in Precambrian banded iron-formations (BIFs) and stromatolites. The investigation of ancient sedimentary sulfide trace metals carries the added dimension that in the case of sediments older than about 2.32 Ga – and prior to the oxygenation of the surface zone – sulfur minerals also have the potential to host mass-independent sulfur isotope signatures (MIF).

There is little doubt that major changes over Earth history in the structure and composition of microbial populations (and later, Eukaryotic populations) have induced profound effects on the geochemical cycles and seawater concentrations of the bio-essential elements (S, P, O, N, C, H, Fe, S, etc.) as well as those trace metals (e.g. Ni, Co, Cr, Zn, Mo, Mg, Mn and others) that figure prominently in life. Yet how (and when) have concentrations of these seawater trace metals changed over geologic timescales in response to changes in the Earth System, such as the rise of oxygen, the collapse of methanogens and the demise of MIF sulfur?

Our new methodology can differentiate the source(s) of sulfur to BIF and stromatolite sulfides from volcanic sources, aerosols, or sulfate reduction (either microbially mediated, or via thermochemical processes) through multiple sulfur isotopes studies coupled with trace-metal concentrations through time. We report the chemistry of sulfide mineral precursors via the experimental determination of adsorption of dissolved metal species on to colloidal reduced-sulfur particles (either derived from aerosols, or from reductions of S⁰ and sulfate to H₂S via microbial processes) as a “meter” for paleo-seawater trace metal compositions. The likelihood that metabolic cycling of the sulfur occurred prior to lithification is tracked by multiple sulfur isotopes (expressed in +Δ³³S as a possible fingerprint of elemental sulfur reduction, ESR; -Δ³³S in microbial sulfate reduction, MSR) as well as ranges in S⁴⁴/S³₂S ratios conventionally expressed in δ³⁴S (vs. VCDT). We report on transformations of sulfides in diagenesis of the BIF and stromatolites, and the preservation of the trace-metal and MIF signatures in the sulfides in rocks that have experienced varying degrees of metamorphism. Our database shows that much like Ni/Fe in BIFs through time (Konhauser et al., 2009), there is a co-relation of trace metal signatures (expressed in molar ratios of Ni, Co, Cr, Cu, Zn, Mo, Mg, Mn vs. Fe) and MIF to secular changes in the redox state of the surface (ages where possible will be determined from Pb-isotopes, or if feasible Re-Os, geochronology). Finally, these data are used to explore the tempo of oxidation of the surface zone possibly associated with changes in marine microbial community structure perhaps in response to the (relatively late?) appearance of oxygenic photosynthesizers (i.e. cyanobacteria).
The geophysical effects of Enteromorpha mats on siliciclastic beach sediments

John Murray, Azra Meadows, Peter Meadows

Enteromorpha forms dense localised algal mats on siliciclastic sediments in the intertidal zone of low and medium energy coasts. The mats are layered into the sediment on an annual basis and can be readily detected below the sediment surface, where they provide micro-environments for sulphate-reduction and microbial activity. We have investigated the effects of these mats at and below the sediment surface on the geophysical properties of sediments. We have used miniaturised equipment to detect heterogeneity in the strength of the sediment on a microscale level. The implications of this microscale geophysical heterogeneity for the long term stability of the mats, and for the interaction of the mats with microbial and infaunal sedimentary communities at different scales, are discussed.
EVIDENCE OF MICROBIAL MATS IN ANCIENT GONDWANA GLACIGENIC FRASHWATER LAKES

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Microbially-induced sedimentary structures (MISS) are well documented in both modern and ancient siliciclastic shallow marine, tide-dominated deposits, but their occurrence in freshwater environments is rarely reported. Also, although microbial communities can be very successful in all habitats, the good preservation of MISS occurs preferentially in stressed environments where bioturbation activity has no or little chance of developing. Wrinkle structures and biolaminations are abundant in the Gondwana glacigenic deposits of the Itararé Group (Upper Carboniferous-Lower Permian, Paraná Basin), cropping out in southern Brazil. These deposits consist of different arrangements of massive shales, diamictites, rhythmites, and fine- to medium-grained sandstones with trough cross-stratification. Two genetically distinct thickening-, locally coarsening-upward successions of tabular rhythmites belonging to the Mafra Formation can be distinguished in the Mafra/Rio Negro region (Santa Catarina and Paraná states), representing the landward portion of an incised valley filled during deglacialiation. These rhythmites are represented by couplets composed of millimeter-scale mudstone beds and millimeter to centimeter-scale siltstone beds. Three MISS morphologic patterns can be recognized: mat surface structures (elephant skin), mat subsurface structures (Kynneia and trapping and bidding structures), and mat deformation structures. Optical microscopic analyses revealed the presence of irregular network structures in the interface between mudstone and siltstone beds, and linings, amorphous organic matter concentrations, and sinuous biolamination structures in mudstone beds. SEM images show thin filamentous material dispersed between the sediment grains. A low diversity ichnofauna also occurs in the Mafra Formation rhythmites, overprinting the MISS. Two ichnocoenosis can be diagnosed: (i) a freshwater Mermia ichnocoenosis, formed by tiny shallow burrows (Cochlichmus anguineus, Cruziana cf. problematica, Gordia arcuata, Gordia marina, Hormosiroidea meandrica, Rusophycus cf. carbonarius, and Treptichnus pollardi), swimming fish trails (Undichnia consulca) and intermittent rusophiciform traces, preserved in the upper couplet beds; (ii) a terrestrial atypical Scoyenia ichnocoenosis, composed exclusively of delicate miriapod trackways (D. gouldi and D. biformis), which occur in all ichnofossiliferous paired mudstone-siltstone of the basal sets of the rhythmite succession, and in almost all of the upper sets, overlapping the Mermia ichnocoenosis, in palimpsest preservation. The rhythmic deposition suggests distal underwater gravity-flow deposits, forming shallow lakes or ponds in depressed areas, the siltstones deposited by melting currents and the mudstones by sediment fall-out, after the flux ceased. The abundant wrinkle structures and the presence of the Mermia and Scoyenia ichnocoenoses suggest a quiet freshwater environment. Most of the burrowers grazed or undermined the macrobial mats during climate amelioration periods, and the sediment stabilization promoted by these mats was possibly the factor that favored the preservation of so delicate trace fossils. Overlying deposits bearing a brackish-water ichnofauna and marine fossils suggest the proximity of a coastal setting, connected with the sea. Although atypical, the occurrence of a Scoyenia ichnocoenosis in almost all ichnofossiliferous rhythmite couplets, preserved over wrinkle structures or overlapping Mermia ichnocoenosis, suggests that these shallow lakes were episodically dried up, at least partially. Regardless of all organic evidences in mudstone beds, the total carbon content is low (0.3% in basal sets, 0.4% in upper sets), suggesting oxidation of the organic matter, which reinforces this hypothesis.
Organosedimentary structures of Archean age in a pre-impact high-grade rock within the Dhala impact structure, central India

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The organosedimentary rocks of Archean age are rare and are known from about 50 locations worldwide. The present study reports organosedimentary structures in pre-impact lithology (N25°18′33.7″, E78°05′0.6″) observed about 6 km WNW of the recently discovered Dhala impact structure (N25°17′52.9″, E78°08′28.91″; Pati et al., 2008) of Paleoproterozoic age (Pati et al., in press) with a minimum estimated diameter of about 11 km. This organosedimentary rock occurs as a metasupracrustal lithounit within Archean Bundelkhand craton (ABC) and intruded by granodiorite-diorite of Archean age. The organosedimentary rocks occur as variably tilted blocks and slabs forming a gentle undulatory topography partly covered under alluvium with an exposed outcrop area of about 1.5 sq km and a trend of N310°. The rock is bluish white in color with alternating moderate to dark blue colored alternating bands of variable thickness (<1 to ≥5 cm). The bands are flat, wavy, and wrinkled to crenulated in shape similar to those observed in MISS (Noffke, 2009). The light colored bands are very fine grained in the mesoscopic scale predominantly composed of quartz. In addition to quartz, the optical and EPMA data indicate the presence of plagioclase (Ca-rich) + augite + hornblende + orthoclase + sphene + zircon + calcite (rare) in this metamorphosed “impure marl” like rock. A penetrative fabric with polygonization is also observed in thin-sections. Preliminary data suggests the rock to have undergone at least upper amphibolite facies metamorphism. The organosedimentary structures occur as flat-laminated mats to strongly convex type. In cross section, they look like domical laminites to small crested/conical laminites and cuspat swales to large complex cones. In places ripple-like wrinkle structures are also observed. There are outcrops showing structures similar to polygonal shrinkage cracks. This finding is extremely significant since this is the first report of possible organosedimentary structure of possible Archaen age in a high grade metamorphic rock from the central part of the ABC and the fact that this organosedimentary structures-bearing rock occurs within the largest complex impact structure (Dhala structure) in SE Asia which has registered shock pressure up to ~60 GPa.

Acknowledgements: JKP thanks Nora Noffke for her continued encouragement and support and the PLANEX Programme, Department of Space, Government of India, for funding the study related to the Dhala impact structure.

References:


Fossil bacterial cells in anoxic Early Miocene shales – synsedimentary bacterial communities or postsedimentary invaders?

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Mineralized bacterial cells have been found in Early Miocene (Aquitanian) fossil-rich shales in the Central Paratethys Sea (Central Europe). Out of a 3-m-thick succession an 8-cm-thick, laminated rock sequence within a “Konservat-Lagerstätte” has been studied by high resolution sampling (one sample per 0.5-1 cm). In order to describe and interpret the preserved bacterial cells a combination of SEM-imaging, qualitative EDX-analyses and geochemical analyses (TOC, S) was conducted. The cells occur as single microspheres with a diameter of 1-2 µm or arranged to chains along filaments. Elemental composition of the cell walls indicates calcitic mineralization.

The data suggest a homogenous organic-rich and poorly oxygenated paleoenvironment recorded by the shales. The mineralized cells are restricted to several centimetres of sediment above a huge sunfish fossil recovered from the rock. Because no bacteria were found around other similarly well preserved fossils of cephalopods, bryozoans and bivalves in the same section it is unlikely that they represent a microbial community autochthonously bound to the decaying carcasses. These microbes are rather interpreted as postsedimentary invaders of the deposits and could represent therefore members of a (sub)fossil deep biosphere. A comparison with allochthonous bacterial cells from the Middle Miocene Monterey Formation (California) further supports the postsedimentary interpretation. In contrast, a synsedimentary community of anaerobic Fe- and sulphate reducing bacteria is indicated by the frequent occurrence of framboidal pyrite in all samples.

These time-averaged mixed bacterial assemblages call for careful consideration of a possible contamination by a much younger deep biosphere when interpreting bacterial fossils in sedimentary rocks.
### Criteria for distinguishing microbial mats and earths

_by Gregory J. Retallack, Department of Geological Sciences, University of Oregon, Eugene, 97302 USA_

<table>
<thead>
<tr>
<th>Microbial mats</th>
<th>Microbial earths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Also known as pond scum, periphyton, algal lamination, stromatolite</td>
<td>Also known as biological soil crust, cryptogamic earth, “old elephant skin”</td>
</tr>
<tr>
<td>Modern: Otematata, New Zealand: Black Rock Desert, Nevada; Everglades, Florida</td>
<td>Modern: Balranald, NSW: Canyonlands National Park, Utah; Kalbarri, Western Australia</td>
</tr>
<tr>
<td>Ancient: Fisher Formation (30 Ma), Oregon; Green River Formation (50 Ma), Wyoming; Brockman Iron Formation (2470 Ma), Western Australia; Strelley Pool Formation (3350 Ma), Western Australia</td>
<td>Ancient: Tumblagooda Sandstone (460 Ma), Western Australia: Grindstone (484 Ma), Uratanna (542 Ma), and Rawnsley (555 Ma) Formations, South Australia; Stirling Range Formation (1900 Ma), Western Australia</td>
</tr>
<tr>
<td>Parataxonomic names: Kinneyia, Baicalia, Conophyton, Thyssagites, etc</td>
<td>Parataxonomic names: Rivularites, Funisia, Aspidella, Dickinsonia, Ediacaria, etc</td>
</tr>
<tr>
<td>Non-adhesive to substrate</td>
<td>Intimately mixed with substrate</td>
</tr>
<tr>
<td>Redeposited as sheets and rollups</td>
<td>Individual organisms redeposited singly</td>
</tr>
<tr>
<td>No hydrolytic weathering of substrate</td>
<td>Hydrolytic weathering of substrate</td>
</tr>
<tr>
<td>Abrupt mineral-texture contrast with substrate</td>
<td>Gradational mineral-texture contrast with substrate</td>
</tr>
<tr>
<td>Substrate cracks passively filled or absent</td>
<td>Substrate cracks with clayskins or oxidized (cutans)</td>
</tr>
<tr>
<td>$\delta^{13}C$ of carbonate $&gt; -2%$</td>
<td>$\delta^{13}C$ of carbonate $&lt; -2%$</td>
</tr>
<tr>
<td>Salt crystals or nodules displacive</td>
<td>Salt crystals or nodules replacive</td>
</tr>
<tr>
<td>Stromatolitic and tufted when thick</td>
<td>Subdued relief and unlayered when thick</td>
</tr>
<tr>
<td>Smoothing over desiccation cracks</td>
<td>Enabling desiccation cracks in sand</td>
</tr>
<tr>
<td>Syneresis cracks (deep U-section)</td>
<td>Desiccation cracks (deep V-section)</td>
</tr>
<tr>
<td>Domed or tufted growth centers</td>
<td>Peripherally sutured growth centers</td>
</tr>
<tr>
<td>Mounded and dimpled with expansion</td>
<td>Pressure ridges with expansion</td>
</tr>
<tr>
<td>Lake or marine gray shale or limestone facies</td>
<td>Pyritic intertidal, red bed, or calcrete facies</td>
</tr>
<tr>
<td>Associated current ripples, rills, normal grading</td>
<td>Associated setulfs, climbing translant wind ripples</td>
</tr>
<tr>
<td>Aquatic-marine, submerged when alive</td>
<td>Intertidal, perilacustrine, soil, rock outcrop</td>
</tr>
</tbody>
</table>
Understanding the morphogenesis of early Archean stromatolites

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The oldest evidence for microbial activity on the ancient Earth comes from stromatolites from the Pilbara craton of Western Australia. Although the steady-state construction of these structures is plausibly attributed to bacterial photoautotrophs, the more interesting question is how did they originate in the first place?
Wrinkles, Dimples, and Steps - Sedimentary Features Produced by Extracellular Polymers in Non-filamentous Biofilms

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In experiments, biofilms of coccoidal cyanobacteria developed on sand surfaces that were submerged under a few centimeters of water. The sand surface was stabilized by gelatinous extracellular polymers (EPS) that were secreted by the cyanobacteria (order *Croococcales*).

Although soft and easily disturbed, the gelatin-bound surface offers resistance to erosion by waves and rain drop impacts. When the biofilm is freshly exposed, short rainfall breaks up the bound surface into a series of irregular ridges that consist of a mixture of EPS and coccoidal cyanobacteria. Longer lasting rainfall will completely mix the surface EPS with sand from deeper layers and obliterate the bound surface layer. Waves can erode and undermine mucous bound surfaces and produce erosional edges and pebble-size fragments of mucous bound sand.

Once exposed to the air, the mucous bound surface film gradually dries out and hardens. Upon re-wetting, the surficial layer of mucous and sand begins to swell and develops expansion ridges and an irregular network of surface wrinkles. These are in appearance quite similar to wrinkle marks described from filamentous microbial mats.

If biofilms that develop the above structures are rapidly buried under sand, the surface relief should be molded into the base of the overlying sand bed. Because of the presence of easily digested organic matter on this surface there is a potential for formation of diagenetic minerals (such as pyrite or siderite) that trace the boundary and preserve it in the rock record.
Evidence for Life on Land ~1100 Ma Ago

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The Keweenawan Mid-Continental Rift event ~1100 Ma ago resulted in the accumulation of thick (km-scale) packages of continental clastic sediments that are exposed today at the margins of Lake Superior as part of the North Shore Volcanic Group (Minnesota) and the Powder Mill Group (Wisconsin, Michigan). Within those sediments, there are a variety of depositional environments including lacustrine, paludal, and fluvial facies along with paleosols and stromatolites. Both the paleosols and stromatolites contain evidence of microbial mat structures (e.g., *Kinneyia* structures), including the preservation of both organic (North Shore Volcanic Group) and carbonate (Powder Mill Group) structures. There are relatively few reports of life on land in the Archaean, none in the Paleoproterozoic, and evidence for life on land in the Mesoproterozoic has been limited to rare microfossils in alluvial deposits, rare cryptoalgal stromatolites preserved between clasts in alluvial deposits and probable microbial sedimentary structures, so these extensive microbial structures from the Keweenawan Rift represent a significant expansion of the Precambrian record of microbial structures in clastic sediments. In addition to the sedimentological evidence, organic carbon isotopic evidence for an extensive terrestrial biosphere is present in the paleosols and associated sediments from the Keweenawan Rift (USA). The organic matter is preserved throughout a 65m section of intrabasaltic sediments in the North Shore Volcanic Group in paleosols and microbial mats, and as detrital carbon in laminated fluvial sediments. $\delta^{13}C_{\text{org}}$ values range from -29.6 to -25.5‰, suggesting oxygenic photosynthesis. The contemporaneous Powder Mill Group on the Keweenaw Peninsula (Michigan) preserves riverine stromatolites that range in size from cm- to dm-scale. These results, from both sides of a continental-scale rift system, establish the presence of extensive microbial life on land ~1100 Ma ago.
Ecological diversity of microbially induced sedimentary structures (MISS) in the Mesoproterozoic North China Platform

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The North China Platform preserves one of the best-exposed Mesoproterozoic successions in the world, with a total thickness of > 8 km. Recent studies in this succession identified a plethora of microbially induced sedimentary structures (MISS) that show temporal and spatial variations across the sedimentary facies. While microbial laminae appear in most depositional environments, the ecological diversity of MISS is controlled by depositional environments. For example, in backshore and tidal flat environments, due to periodical and long-term subaerial exposure of the sedimentary substrate, fully developed polygonal cracks and gas blisters are the most abundant. In high-energy shoreface environments, sand chips, large pocket marks and mat-protected ripple marks are proportionally high. In low-energy subtidal environments, mat roll-ups, Kinneyia structures, and mat growth structures usually have more chances to be preserved. The ecological diversity of MISS records information on microbial colonization of sedimentary substrates, sedimentary supply, tidal and wave energy conditions, and micro-environmental carbonate saturation state. Detailed ecological study of MISS may serve as an important tool for understanding interactions between microbes and depositional environments and potentially, the secular climate changes during the Mesoproterozoic.

Keywords: MISS, ecological diversity, climate change, Mesoproterozoic, North China platform
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A preserved Late Cretaceous biological soil crust in the capping sandstone member, Wahweap Formation, Grand Staircase-Escalante National Monument: Paleoclimate implications

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Modern biological soil crusts develop under semiarid to arid conditions and are characterized by a diverse community of microorganisms. Outcrop of the Late Cretaceous capping sandstone member of the Wahweap Formation in Grand Staircase-Escalante National Monument, Utah, contains what is best interpreted as a preserved biological soil crust. This paper describes this rarely reported soil type from the rock record and discusses the paleoclimatic implications.

The capping sandstone of the Wahweap is separated from the overlying Kaiparowits Formation by a change in lithology from quartz arenite to lithic arenite, and a change in paleocurrent direction from southeast to northeast. The biological soil crust is developed about two meters below this contact and covers an area about 20 meters by 5 meters. The soil features, in profile, vary from 10 to 15 cm thick. The surface morphology is pedicillated with mm- to cm-scale irregular prismatic columnals, and is strikingly similar to that of modern microbiotic soils. Small deep tracks preserved within the underlying layer demonstrate that the soil was easily penetrated. In thin section, the quartz arenite is poorly sorted, displaying a range in grain size from silt to medium-grain sand in contrast to the well sorted sandstones elsewhere in the capping sandstone. Porosity is highly variable with high porosity zones attributable to bioturbation. No direct evidence is preserved of the former microbial community, except for a mottled color pattern in the thin section sans magnification. In close association with the biological soil crust are medium-scale low-angle eolian cross-beds. The biological soil crust was possibly preserved by eolian burial. This combined evidence strongly supports a semiarid to arid climate in the uppermost capping sandstone member of the Wahweap Formation.
Flat laminated microbial communities and the sedimentary environment

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Flat laminated microbial mats are complex microbial ecosystems that often inhabit silicoclastic environments. Their community structure is defined by physical (e.g., light quantity and quality, temperature, density and pressure) and chemical (e.g., oxygen, oxidation/reduction potential, salinity, pH, available electron acceptors and donors, chemical species) factors and species interactions. These communities are dynamic systems often exhibiting spatial and temporal heterogeneity, and steep gradients with microenvironments on the submillimeter scale. Flat laminated microbial mats are often sites of robust biogeochemical cycling. In addition to well-established modes of metabolism for phototrophy (oxygenic and non-oxygenic), respiration (both aerobic and anaerobic), and fermentation, novel energetic pathways have been discovered (e.g., respiration of arsenic and selenium oxyanions). These microbiological processes can result in unique sedimentary structures and mineral deposits.
Microfossils from nonmarine siliciclastic mats from the late Mesoproterozoic Torridonian Sequence, NW Scotland.

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The Torridonian sequence (ca. 0.9 to 1.2 Ga) is a nonmarine, coarse siliciclastic, largely redbed sequence in the northwest Scottish Highlands. Minor grey shales and associated phosphatic beds/nodules have long been known to harbor microfossils, but this is the first comprehensive study of any terrestrial communities of Precambrian age. We sampled over 50 horizons of fossiliferous shales, which upon acid maceration, yielded a diverse array of organic walled microfossils (OWMs). Sphaeromorph acritarchs dominate the assemblages, but we have also recovered a wide array of organic remains that represent far more than simple "algal cysts." These include enclosed multicellular clusters, colonial and seemingly multicellular forms, various filamentous sheaths, simple structural organic remains such as spines (?) and cuticles, and other complex forms. At Lower Loch Diabaig, a sequence of over 800 beds thought to represent subaerially exposed siliciclastic microbial mats, developed in an ancient freshwater lake. We compared samples from desiccation cracks of varying sizes with in situ samples from these reticulate (elephant skin) microbial mat textures. Even though these fabrics are extremely well-developed, the organic remains associated with these ancient mats are allochthonous in character. For example, fragmentary filamentous sheaths observed in bedding parallel thin sections are scattered nearly uniformly over bedding plane surfaces. Organic-rich clods recovered from desiccation infillings contain filamentous sheaths and small Chroococcalean cells which bear a strong resemblance to members of the extant Halothece/Euhalothece group of halotolerant cyanobacteria. These appear to be locally-transported examples of the organisms that inhabited the reticulate mats. Variation in preservational quality also indicates that a wide range of microhabitats have been sampled by these ancient muds, ranging from adjacent microbial mats to upstream fluvial and marginally fluvial subaerial habitats. Eukaryotic remains clearly dominated these nonmarine assemblages however, implying that terrestrial habitats may have played a far more significant role in the evolution of early eukaryotes than previously thought.
Sandballs from the Dahongyu Formation (ca 1.65Ga) of the North China Platform: Refilled gas dome origin in a foreshore environment

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The Dahongyu Formation of the Lower Changcheng Group is widely distributed in the North China platform and consists of quartz sandstone and siltstone deposited from peritidal environments. In this formation, abundant sandballs of 1-3cm in diameter have been recognized in several sections. The balls themselves consist of muddy sands, with siderite and hematite recognizable in the argillaceous matrix, while the host rock is relatively pure in composition and mainly composed of well-sorted, medium-sized quartz grains. On weathered bedding planes, the balls show biscuit-like positive relief with clear concentric layers expressed by alternation of sands and silts. In vertical section they also display rounded shapes rather than tubes, with clear margins separated from the host quartz sandstone. After a thorough study on the morphology and mineral composition of the balls from different places, these sandballs were best interpreted as gas domes formed by CO₂ degassing from organic matter decay, which were refilled subsequently during low-energy environments after exposure. The sandballs are thus considered as a type of microbially induced sedimentary structures (MISS); their widespread occurrence in episodically exposed environments may indicate that microbial community started to colonize nearshore to terrestrial environments in the Paleoproterozoic.

Keywords: sandballs, gas-domes, MISS, Paleoproterozoic, North China platform

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Evidence of microbial activity on early Tertiary sediments, Andes foothills, Argentina

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The Pichaihue section is located in the inner Agrio fold and thrust belt in the retroarc Neuquén Basin of Argentina (36°40’ South lat.). It is composed by volcanic and volcaniclastic rocks caped by calcareous sediments that were interpreted as being deposited in a lacustrine to shallow marine environment related to a Maastrichtian-Danian Atlantic transgression. The facies of the Pichaihue Limestones include massive bioclastic mudstones with calciespheres, laminated stromatolites, oncolites and macrophytes. The microbial activity was suspected from outcrops and through thin sections, and SEM analysis showed undoubtedly the presence of cyanobacterial filaments, nannobacteria and coccoids microbes that clearly support the microbial origin. We identified smooth to lumpy surfaces and forms that range from tiny spheres to stubby ellipses and long filaments. The filaments and some of the tiny spheres are coated by aggregated of small (less than 0.5 um) anhedral equant calcite crystals. It is known that the microbial films contribute to stabilization of the sediment and preservation of biogenic structures. In our study we propose that the microbial films avoid the destruction of the relief under intertidal conditions and also preserve the macrophytes stems. Recent works in the Neuquén Basin described a microbial reef in sediments of the same age cropping out 20 km to the northeast of our study area, but no evidence on nannobacteria was mention there. This contribution supports their proposal and also the idea that after a major extinction (K-P in our case) special environmental characteristics are suitable for the development of microbial communities (Ezaki et al. 2008). Those communities are quickly disrupted when normal marine conditions are re-established.

Living to Lithified: Microbial Preservation Potentials in Yellowstone National Park

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Actively-lithifying microbial mats in Yellowstone National Park (YNP) show a dramatic bias to preserve only a few types of microbes even though culture independent molecular surveys that indicate the living mat is comprised of a diverse assemblage of microorganisms. Preferential preservation is a problem in evolutionary science; it suggests that the oldest known fossils on Earth, fossilized microbial mats, may present a skewed view of ancient ecosystems and environments. Little data exists on mechanisms for microbial mat fossilization or the preferential preservation of certain microbes. While silica precipitation may be dictated by chemistry, the fact that only certain microbes are silicified implies that silica binding to microbe surfaces is biologically-mediated. The most commonly silicified microbes are cyanobacteria with thick polysaccharide sheaths composed of extracellular polymeric substance (EPS), which may bind silica preferentially and increase preservation potential. However, many microbes produce EPS, raising the question of how EPS is related to silica binding.

This work includes both laboratory silicification experiments to compare the amount and chemistry of EPS for given YNP microbes to the extent of silicification to determine preservation potentials, and the characterization of a unique geobiological formation in the Sentinel Meadows area of YNP. The site consists of an active silica-precipitating hot spring surrounded by living microbial mats, which overlays over twelve meters of laminated, lithified microbial mat. Due to a rock fall, over ten vertical meters of lithified mat sequence is exposed, allowing us to construct vertical profiles of morphology, chemistry, and rates of silica precipitation and microbial fossilization. Work shown herein is applicable the study of mineralization in hydrothermal environments, lithified mat deposits, microbial fossilization and preservation, and the interpretation of evidence of the origin of life on Earth.
Evidence for the First Emergence of Metazoan-Microbial Reef Consortia

Estee Woon

The nature of the transition from a largely microbial world of the Precambrian to a Metazoan world in the Phanerozoic has attracted much attention and debate. The recently discovered Cryogenian-aged Oodnaminta Reef from the northern Flinders Ranges, South Australia (deposited between ~658-635 Ma), is well placed in the Precambrian geological record to assess the nature of these significant shifts in the biosphere in the context of reefs and reef-building organisms.

The deep-water reef-margin of this Oodnaminta Reef is constructed by two previously undescribed organisms, which is interpreted in this study to be heterotrophic, Metazoan-like, multicellular organisms. These bear similarities to “primitive” organisms: sponges, corals and to some extent, calcified microbes. The employment and merging of typically “primitive” Metazoan characteristics observed in these organisms can be attributed to their occurrence at the earliest period of Metazoan evolution and the almost certainly limited range of body-plans available during this time.

These Metazoan-like organisms display a very close associations and interdependencies with recognisable microbial constituents (carbonate shrubs, thrombolites and stromatolites) in the reef framework. Indeed these associations compare well with other Metazoan-microbial reef assemblages in the latest Precambrian and in the Phanerozoic. The age of the Oodnaminta Reef and the nascent characteristics of its metazoan constituents suggest that this would be one of the earliest occurrences of a Metazoan-microbial reef assemblage and consequently a significant milestone in the evolution of the biosphere from microbial toward Metazoan.