Chapter 1

BIOFILM, BIODICTYON, BIOMAT MICROBIALITES, OOLITES, STROMATOLITES GEOPHYSIOLOGY, GLOBAL MECHANISM, PARAHISTOLOGY

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1. INTRODUCTION

This article is conceived as an introduction to “Fossil and Recent Biofilms”. Fossil and recent microbial communities adhering to, overgrowing and enmeshing inorganic substrates are introduced. The biofilm substrates embrace rocks and minerals exposed to the atmosphere or to overlying water bodies of different salinity and include deeply buried sediments and rocks. Biofilm communities active in soil, sediment and rock interstices, cavities, cleavages, and cracks until deep into the Earth crust are dealt with. Definitions and common traits of a biofilm, biodictyon and biomat (microbial mat) are presented and discussed. Fossilised examples as well as ichnofossils (trace fossils) of extant communities are sketched. Some science history reflections are included. New terms such as biodictyon, geophysiology, parahistology, and global mechanisms of microbial communities in past and present planetary ages are defined. The intimate relationship between major rock types such as biolaminated sequences (and ore deposits), stromatolites, oolites, onkolites and also reef type deposits is discussed. The planetary and exobiological dimension and global importance of biofilms, microbial mats and network microbial communities are noted.

2. HISTORY AND EVOLUTION OF TERMS

The first clear and lucid report of field observations and laboratory experiments on biofilms and their rock generating potential stems from Paracelsus (Krumbein, 1993a, 1994; Paracelsus, 1528, 1982). However, Maxim 524 of Titus Livius clearly demonstrates that knowledge existed long before: "Rolling stones gather no moss, i.e. biofilm growth" (which the Rock-Band "Rolling Stones" definitely did). Paracelsus himself wrote:

> "For from the mucilago of the water are growing and born all rocks and all pebbles and sands are coagulated into rocks. This is easily eyeable (visualised) for a mucilago sooner or later attaches to any stone, deposited into flowing water. And upon separating such mucilaginous matter from the rock and depositing it into a cucurbite (a kind of an Erlenmeyer) it will coagulate and transform into a rock just like any rock growing in the natural water by self-coagulation and genesis after a long period of time".

Thus Paracelsus did, what happens today in many biological, ecological or geoscience Institutes: Biofilms and microbial mats are observed in field and laboratory experiments. Hereby the modern scientist makes the same observations as our ancestor in science. Namely we observe and bias the formation of biofilms and microbial mats and their eventual transformation into e.g. sedimentary rocks in field and laboratory.

Microscopic evidence of rocks produced by microbial mats was published quite early (Brückmann, 1721; Hooke, 1665). The latter depicted microbial mats and ooids embedded in them. They were, however, less certain than Paracelsus about the origin of these structures. One of the most interesting transfers from medical science and histology into microbial (and global) ecology seems to be the term glycocalyx derived from the phenomenon in the abdomen of many animals including the human body which was later identified as slimy extracellular substances (EPS) of eukaryotic cells in intimate relationship to cell clusters or biofilms of archaea and prokarya. Such glycocalyx-like slime films were later recognized as biofilms (Characklis and Marshall, 1990; Costerton et al., 1987; Harris, 1972; Marshall, 1976, 1984; ZoBell, 1943). ZoBell (1943) was the first author to ascribe the evolution of biofilms to hydrophobic and hydrophilic characteristics of the outer envelopes of bacteria getting attached to surfaces this way. The extra-cellular material into which the bacteria and also algae and protozoa are embedded embraces extracellular compounds mostly consisting of complex polymers of many different carbohydrates to which phospholipids, proteins (exo-enzymes), and highly polymeric partially phenolic substances (lignin, melanin, carotene, and compounds chemically similar to Maillard reaction products) are added. These extra-cellular, but metabolically, cytological and morphologically important substances represent outer layers of cells beyond membrane and cell wall, the classical envelopes of the cellular machinery of life. They were first named extracellular polysaccharides, later extra-cellular polymeric substances (EPS). Paracelsus called them slime, mucilago, or just "Schnoz" not unlike slime droppings from the nose from which he derived the name *Nostoc* for a biofilm producing cyanobacterium (Potts, 1997).

Paracelsus and others thought it were organic meteorites (chondrites) for hundreds of years. Dried and detached biofilms may be transported by the winds and fall down hundreds of kilometres inland. These were initially interpreted as extraterrestrial bodies or "meteor paper". Chondrites, or paper meteorites were found, collected, analysed and described for about 250 years before Ehrenberg (1839) identified them as wind-blown microbial mats or carpets. The interesting point is, that these gelatinous substances were very rapidly swelling and reviving after heavy rainfalls and thus confused with meteorites. However, the most important and still not clearly settled phenomenon in relation to biofilms and biofilm producing microbes is their capacity to produce large amounts of EPS and excrete them so to say as garbage from the cell. These extracellular products in many cases of biofilms and microbial mats make up more than 99 % of the total metabolic products (Cooksey, 1992; Decho, 1990). The idea of slime as a living agent was very productive on the one hand. On the other hand the multiple lines of thought around evolution, spontaneous generation, bacteria as "chemical enzymes" and diseases generated from dirt and mud lead to many an erroneous observation, hypothesis and scientific debate. The most fascinating and heated debate lasted only 7 years and dealt with *Bathybius Haeckelii* (Haeckel, 1877; Huxley, 1868). The "tragic rise and descent of *Bathybius*" was described to some detail by Krumbein (1984). Mucilaginous networks of "living material" were described by Huxley from samples of the Challenger expedition. Huxley named this protoplasmic substance or organism in relation to the monograph of Haeckel on Monera in his name. The original English publications contained the German word "Ur-Schleim" best translated as "primordial living soup or super-organism". It was, however, quite quickly found, that it was an artefact and Haeckel (1877) himself had to admit that a world embracing organism in the sense of Hutton's Super-Organism Earth (Lovelock, 1969) was not existing. Biofilms and microbial mats, however, today take this position as a worldwide ubiquitous power driving mainly the geophysiology of Earth (Krumbein and Schellnhuber, 1990, 1992).

Marshall (1976, 1984) and later Costerton et al. (1987) introduced the term biofilm into biotechnology and microbial ecology. Doemel and Brock (1974, 1977), Krumbein, 1978, and Krumbein et al., 1977a, b) slowly transformed the misleading term “algal mat” into bacterial mat and microbial mat and biofilms as the driving forces behind the formation of microbial sediments and sedimentary rocks (Riding and Awramik, 2000). This was necessary, when blue-green algae turned out to be cyanobacteria (Krumbein, 1979; Krumbein et al., 1979b; Rippka et al., 1979). A merger process started between the geological literature on oolites and stromatolites and the microbiological literature on biofilms and microbial mats (Krumbein, 1983a). This process is still in progress (Brehm et al., 2003). One result of cross-boundary research was a change from the study of individual microbial cells floating separately in water (plankton) studied in liquid and isolated agar culture to a sophisticated systemic approach in the study of surface attached biofilms and mats. This was initiated by Ludwig and Theobald (1852), critically explored by Weed (1889), ZoBell (1943) and introduced into laboratory scale experiments by Caldwell and Hirsch (1973) using chemical gradient agar surface film studies as a new experimental approach. Ludwig and Theobald (1852) in their classical underestimated and thus unnoticed paper added another facet to the fascinating question of the behaviour of benthic surface microbial communities, which only now starts to be elucidated by several research groups. Within many mats and biofilms a change of organisation is observed from a gradient oriented laminated community (biofilm, microbial mat, potential stromatolite) into separate sub-systems within a generally two-dimensional biofilm or multiply laminated microbial mat (Ludwig and Theobald, 1852; Krumbein and Cohen, 1974). This change of organisation creates three-dimensional spherical communities regulated mainly by the community and the signals sent out by the individual members within it (Brehm et al., 2003). Hereby spherical units are formed within a laminated system. These microbial symbiotic spheres, when solidifying into rock generate ooids and oolites within or outside of the context of a microbial mat (petrified as stromatolite or biolaminite). It is the great achievement of early workers (Brückmann, 1721; Ludwig and Theobald, 1852; Kalkowsky, 1908) to have clearly recognised the intimate relationships between laminated and spherulitic growth and the final petrified rock products. Much earlier the mathematician, physicist and microscopist James Hooke (1665) depicted such microbial organogenic structures clearly featuring biofilm structures in and around ooids (Kettering stone plate). Figures 1-3 demonstrate this quite clearly.

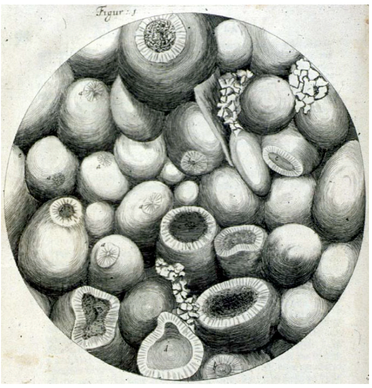

Figure 1: Ooids, fungal mycelium within ooids and fungal remains with attached calcium carbonate crystals around ooids indicating the autochthonous genesis of spherulites within microbial mats (micrograph by J. Hooke, 1665).

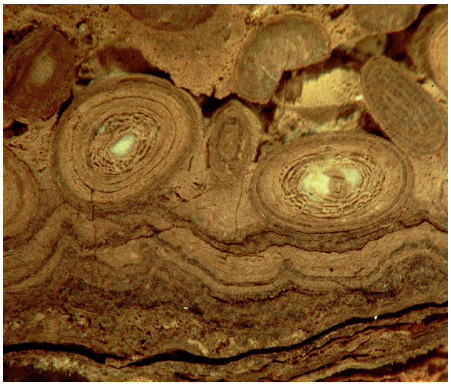

Figure 2: Ooids generated by fungal activity within a microbial mat. The ooids and the associated microbial mat exhibit the same fungal mycelia. Jurassic Minette iron ore (photomicrograph, Krumbein, 1984).

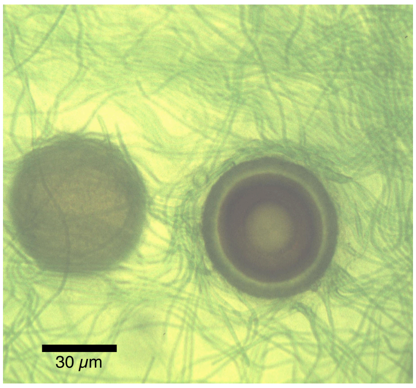

Figure 3: Ooids generated by a biodictyon (a microbial symbiosis between bacteria, cyanobacteria and diatoms from the North Sea coastal Wadden (photomicrograph U. Brehm, 2003).

Figure 4: The first coloured presentation of a laminated microbial mat with individual oxygenic phototroph, anoxygenic phototroph and chemotroph layers (hand coloured micrograph, Flora Danica, 1813).

Biofilms and microbial mats can be regarded as interactive microbial communities thriving in the vertical chemical gradients between sediment and water column, rock and atmosphere, bed-rock and soil etc., creating laminated crusts or rocks (microstromatolite, rock rinds, patina, rock varnish, stromatolite, laminated ore deposits bioliths, biolaminites, erosive and accretionary karst, etc. (Gorbushina et al., 1996; Krumbein, 1983a, Krumbein et al., 1994, Stal and Caumette, 1994; Walter, 1976). The microbial sphere in contrast creates spherical networks and globules and ultimately geological products such as oolites, pisolites, onkolites, and spherulites (Brehm, 2001; Brehm et al., 2003; Kalkowsky, 1908; Krumbein et al., 1977a, b; Krumbein, 1994; Ludwig and Theobald, 1852). The laminated two-dimensional system obviously is an orientated growth of microbes within a vertical chemical gradient modified by the community. In some cases these microbial communities are densely interwoven. In other cases a distinct lamination of different communities occurs. The best studied laminations are known from the Intertidal or Littoral of all coastal water bodies. The first coloured presentation was published in the famous Flora Danica (1813). Figure 4 gives an impressive view of the "Farbstreifen-Sandwatt" (colour striped wadden sediment) with the topmost diatom layer often sealing the surface in a parchment-like way, followed by oxygenic cyanobacteria, anoxygenic phototrophs and then by sulafte reducing and methanogenic bacteria (see also Figures 9-13).

The spherical three-dimensional system obviously is an oriented growth and structuring of space through chemical signals or communication systems between micro-organisms imposing their signals and rules to the general chemical and physical environment. The term was introduced by us in the last years (Brehm, 2001, Brehm et al., 2003; Gorbushina, 2001). The structuring of macro-organism symbiotic communities as described in many communications for bioherms and reefs also reflects a more complex relationship between microbial biofilms and mats and macro-organisms. These also yield three-dimensional geological deposits, often erroneously interpreted as the product of imaginary genera and species. With a growing understanding of the role of biofilms within and on organisms (glycocalyx, karies, termite and cattle digestion system, ulcer, arterial clogging, mykorrhiza, skin flora, hair of the green Polar Bear) and especially in all terrestrial ecosystems above and below sediment or rock surfaces it seems appropriate to state, that biofilms, mats and networks are the most ubiquitous phenomenon and expression of life on Earth. Extraterrestrial biofilms in the frame of planetary biology are also close to our perception, as some contributions in this book seem to indicate. Therefore it is appropriate to move from microscopic to macroscopic in the global biogeochemical connotation of biofilms and microbial mats.

3. BIOFILM

Sub-aquatic biofilm (Characklis and Wilderer, 1989; Costerton et al. 1987; Flemming, 1991; Gerdes et al., 1987; Marshall, 1976)

Three different types of biofilms may be defined, (1) sub-aquatic biofilm, (2) sub-aerial biofilm and (3) biodictyon or microbial network. The sub-aquatic biofilm can be characterised as a layer of more than 99% biologically solidified water (Krumbein, 1993a, 1994; Neu, 1992, 1994), within which a structured community of microbial cells of different genera and species modifies the chemical gradient between a solid surface(s) and the adjacent or overlying liquid and moving water in order to exert metabolic activities maintaining life processes. Solid surfaces or assemblages of larger or smaller-sized rock and mineral particles are covered by a mono-to multi-layered biofilm of microbes. The film develops, may mature and show decay or even detachment at certain moments. The internal structure is complex and has been compared to the structure of larger cities with buildings, shops, streets, canalisation and other specialised units. Neu (1994) claims that biofilms and microbial mats are the same. Other authors insist in making a strict difference between a subaquatic biofilm, a subaerial biofilm and subaquatic or subaerial microbial mats (Krumbein, 1994a, b; Gorbushina and Krumbein, 2000a, b). In that case the biofilm sensu strictu should be regarded more or less as a single layer of organisms within their common matrix (EPS). Mature films develop several layers of organisms. In water processing biofilms even chimney-like structures made of bacterial cells forming several "brick" layers around an aeration channel were observed.

Sub-aerial biofilm (Gorbushina and Krumbein, 1999, 2000a,b)

The sub-aerial biofilm in contrast to the sub-aquatic one is best described as a thin coating of 99% organic matter metabolising in the presence of minimal amounts of active water and surviving for extended periods of time without any supply of liquid water. Rock and mineral particle surfaces exposed to the direct Earth atmosphere or to the gas mixture within a soil, rock, or dune sand system are covered by micro-organisms maintaining an optimum of living cells or a maximum of organic matter in the presence or availability of a minimum of liquid or active water. This community maintains life processes at random intervals of water availability. Practically all surfaces exposed to the atmosphere carry a visible or invisible cover of biofilm communities. These embrace lichen communities, algal films, free living fungi, and bacteria assemblages. All biofilms exposed to a gaseous atmosphere have been identified as capable of forming organic and mineral deposits which have been described already by Darwin (1839) and Humboldt as rock varnish or cataract crusts (see Krumbein and Jens, 1981). These subaerial biofilms, when maturing or vanishing leave structures behind which partially consist of organic polymers such as melanins, carotenoids and chlorophyll derived substances and partially of minerals formed through the activities of the biofilm community. These phenomena are usually described as rock varnish, crust, lichen stromatolite, microstromatolite and by the embracing term patina or biopatina (Dornieden et al., 1999; Gorbushina et al., 2001, Krumbein and Jens, 1981). The organisms involved are to be regarded in many cases as the most astonishing survival experts under extreme and extremely changing environmental conditions. In contrast to the classical extremophile restricted either to very low or extremely high temperature, light, salinity these organisms can withstand and survive also extreme changes of all conditions including extremely long periods of lack of any parameter and compound necessary for metabolic activity. Such communities were recently labled as poikilophilic and poikilotroph biofilms (Gorbushina et al., 1999, 2001; Gorbushina and Krumbein, 1999, 2000a, b). Obviously classical intertidal algal or microbial mats running through extremely changing conditions will also exhibit a large number of poikilophilic microorganisms (Gorbushina et al., 1999).

Biodictyn- microbial network (Brehm, 2001)

A biodictyon is a three-dimensional more or less concentric network of filamentous and unicellular micro-organisms which typically is embedded in soil, sediment or rock. The term was derived from the Greek "bios" for life and "diction" or "diktyon" for net. The biodictyon thus is a living network. Biodictyon may also occur within organic tissue, at certain places of roots (mykorrhyza), within decaying wood (fungal infections) or deep within the deep sedimentary or rock biosphere, where the environmental conditions do not allow for the development of a two-dimensional biofilm or multilayered microbial mat. Within the context of work on intertidal microbial mats, spherical meshworks developing within them were found, which often generate ooids or calcispheres. Sub-aerial biofilms often exhibit typical three-dimensional meshworks and create bio-erosional patterns in the form of biopits (Krumbein and Jens, 1981, Gorbushina and Krumbein 2000a, b). Another typical case of biodictyon formation is reported from many ore deposits. Usually organic matter and other energy sources intrude into pre-existing rock deposits creating cracks and crevices and a system of pores for the percolation of water, nutrients and germs. Within the pore system networks of microbes develop and may ultimately be involved in the creation of rich ore deposits. Such evolution of microbial networks was described recently for a uranium mine in the Black Forest (Germany), where pitch-blende and other uranium minerals were obviously deposited by microbial and especially fungal activity (Hofmann, 1989).

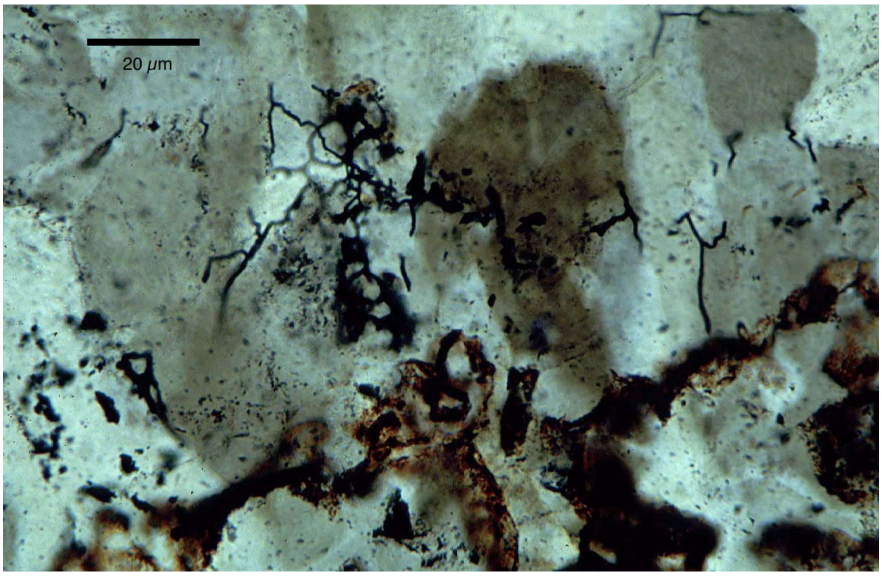

Figure 5: Biodictyon from the uranium deposit Krunkelbach/Menzenschwand, Black Forest (photomicrograph W. E. Krumbein, 1988).

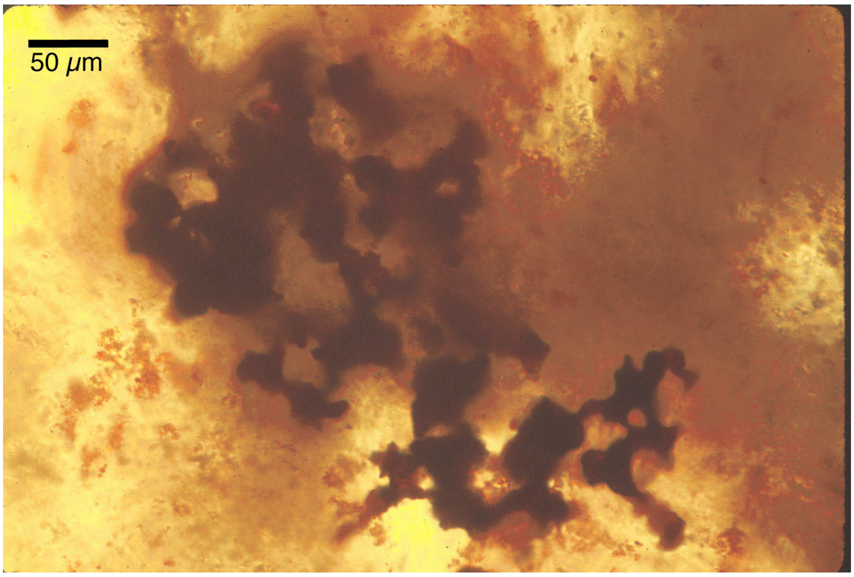

Figure 6: (Bio?)dictyon from the Hammersley banded iron formation (BIF) Precambrian, Australia (photomicrograph Krumbein, 1983).

Descending or circulating phreatic water may have brought organic or inorganic energy sources and micro-organisms to this deeply buried contact zone. The microbes settled at the sites rich in reduced elements. This way a rich microflora developed and infected the rock with a dense network of microbial growth. Figure 5 gives an example of a fungal biodictyon growing about 500m deep below the surface at the contact between the Carboniferous Bärhalde granite and hydrothermal waters ascending in the Tertiary. The microbial per-mineralised network of this uranium deposit is strikingly similar to network structures in the pre-phototrophic world of the Precambrian Hammersley Basin in Australia (Figure 6). Tremendous amounts of iron oxides were deposited in (bio?-) laminated deposits called Banded Iron Formation (BIF). These may have also been deposited by network forming early chemotroph microbial networks. The diameter of the original microbial structures usually is expanded 5 to 10 times by heavy incrustations with iron minerals. This and other rather network or meshwork structured communities we would like to separate from the general picture of biofilms and microbial mats. Such entangled networks were also found by Barghoorn and Tyler (1965) in the Precambrian Gunflint deposits in Canada. Also here it remains doubtful whether phototrophic or chemotrophic biofilms, networks and microbial mats prevailed (see Figures 7 and 8).

4. MICROBIAL MAT, MICROBIAL CARPET, ALGAL MAT, FARBSTREIFEN-SANDWATT, METEOR PAPER

(Black, 1933; Cloud, 1962; Doemel and Brock, 1974; Ehrenberg, 1839; Hofmann Bang, 1826; Krumbein, 1966, 1972, 1983, 1994a, b, 1996; Ludwig and Theobald, 1852; Schulz, 1936).

The origin of all these terms is still not clearly analysed. Without doubt a multilayered microbial community thriving at the sediment water interface and generating rock like deposits was termed an algal carpet (Algenteppich) first by Ludwig and Theobald (1852). Algal mat as a term got very popular, when several teams started to study the potential of rock formation of blue-green algae (later re-named cyanobacteria) in tropical Seas in relation to the modern analogues of Precambrian stromatolites (Black, 1933; Cloud, 1942; Darwin, 1839; Kalkowsky, 1908). Many different definitions and morphological, physiological and geological descriptions of both terms have been proposed and slowly emerged into their individual life. Early work includes also different attempts of definitions and understanding the natural history of these important communities (Black, 1933, Doemel and Brock 1974, Krumbein, 1983a; Walter, 1976). In this context of the evolution of terms it is noteworthy to mention that the referees for the Journal “Science” accepted an article by Doemel and Brock (1974) in which the terms “algal mat”, “microbial mat” and “bacterial mat” were used without any discrimination so to say as synonyms for the Yellowstone Hot Spring microbial mat systems. Film, however, does not occur in this publication. Biofilms thus really have to be seen separate from the multidimensional intimately interwoven microbial mat system of recent or potential stromatolites and biolaminites (Gerdes and Krumbein, 1987). A general definition of microbial mat does not exist. Definitions overlap with the term and description of stromatolites (Kalkowsky, 1908; Krumbein, 1972, 1983a).

Without mentioning the term microbial mat Charles Darwin (1839), Alexander von Humboldt (1793, 1807), Christian Gottfried Ehrenberg (1839) and others described these interwoven mats of organisms as fascinating phenomena in intertidal areas, on rock surfaces, and in caves and mines underground. It is also very noteworthy that the transfer of the cyanophyceae from plants or algae to bacteria was made long before on the basis of microscopy of such algal or microbial mats. Further also the geological potential was noted very early in the history of our science. Ferdinand Cohn (1867) deduced a relationship between groups of bacteria, (Phycochromaceae or Cyanophyceae), red algae, and lichen on the basis of pigments, type of cell division, movement, and mode of reproduction. The pigments chlorophyll, phycocyanin, and phycoerythrin were detected by simple chromatographic and spectroscopic methods. On the basis of Darwin's evolutionary theory as well as his own observations, Cohn proposed that the bacterial phylum Phycochromaceae or the cyanobacteria were early inhabitants of the Earth because of their ability to adapt to extreme habitats, their simple way of reproduction, and the fossil records. He also stated the great similarity between colourless (non-photosynthetic) filamentous and coccoid bacteria, such as *Beggiatoa* , *Thiopedia*, *Thiovolum* and their phototroph counterparts (e.g. *Oscillatoria, Synechocystis*). He studied many biofilm and microbial mat communities including microbial mats and meshworks (photosynthetic and chemosynthetic) in water works, waste water, rivers and soils. Figures 7 and 8 give some insight into the hidden world of a microbial mat as viewed by SEM. In such pictures as well as in thin sections of fossil microbial mats from Precambrian to recent it is always difficult to decide whether the individual organisms are phototrophs or chemotrophs.

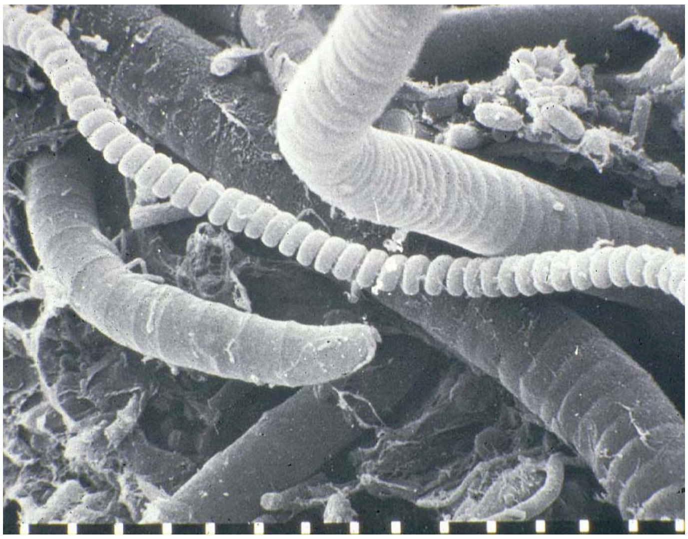

Figure 7: SEM-micrograph of a section of a microbial mat from the Mellum microbial mats. The individual cyanobacteria and associated bacteria form a highly diverse community (photomicro-graph, Krumbein, 1985; bar distance = 3 µm).

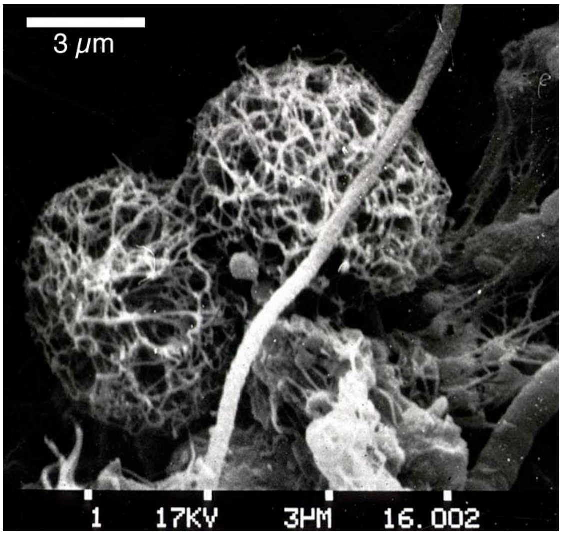

Figure 8: Coccoid heterotroph (?) bacteria from Solar Lake microbial mats, Sinai. The extracellular highly structured material (EPS) leaves doubt about the real size of the microorganism. The organism is not in culture but certainly constitutes an important part of the structuring of the microbial mats (photomicrograph Krumbein, 1975).

Microbial mats are intimately interwoven microbial communities including laminated, concentric and network like growth patterns, which by their upward directed growth, physical and chemical gradients, barriers and sticky EPS products trap and embed mineral grains, produce new minerals and, ultimately, laminated and spherulitic sedimentary rocks and structures (Krumbein, 1983a; Noffke et al, 2001). Many microbial mats (especially in the intertidal zones) enmesh siliceous and carbonate sand and mud in multiple layers. Often they compete with and deeply influence the chemistry of evoporitic salt swamp deposits (Gerdes et al., 1987, Friedman and Krumbein, 1985). As an example a general and four individual diagrams and sketches (Figures 9-13) shall demonstrate the multiple functions of sediment structuring microbial mat communities of a siliciclastic environment in the North Sea Wadden deposits. These multicoloured and multipurpose microbial mats were described very early by Hofmann Bang (1813, see Figure 4) under the title "architects of rocks and islands" and by Schulz (1936) as "Farbstreifen-Sandwatt" (multicoloured laminated wadden sediments). Thus already in the 19th Century the old idea of Paracelsus was revived, namely that micro-organisms build rocks and islands. Also Kalkowsky (1908) suggested, that the origin of his stromatolites and oolites was related to bacterial activity or any other kind of micro-organism. Multilayered and often very complex chimney or dome shaped microbial mats have been found in many lakes, in shallow Seas, near Deep Sea hydrothermal vents and in connection with methanogenesis. Some of them transform into laminated rocks, others decay and release their mineral products and entrapped particles into the water body for new sedimentation. Several interesting Symposia have focussed on microbial mats (Cohen and Rosenberg, 1989; Krumbein, 1978, 1979; Krumbein et al., 1994; Stal and Caumette, 1994). The information is tremendous and new facets are coming up daily.

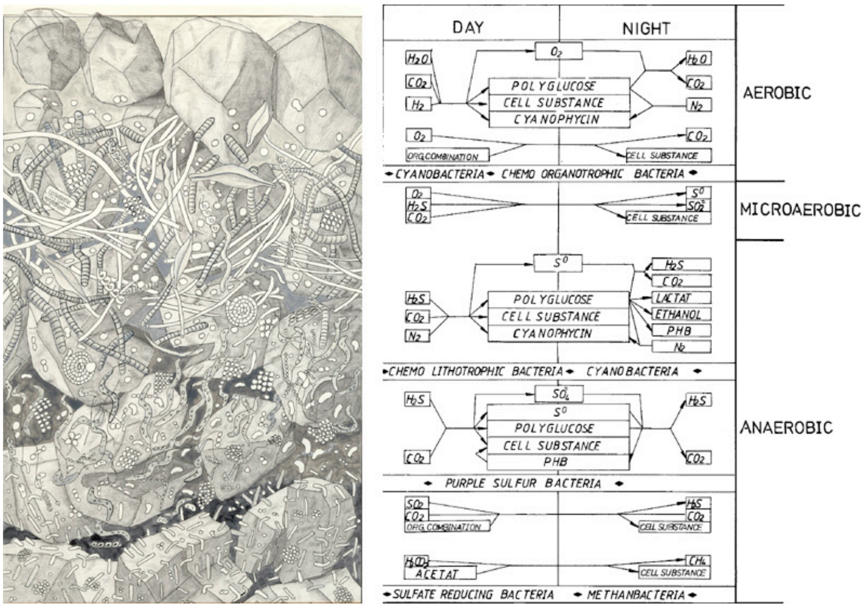

Figure 9: Schematic view of a laminated microbial mat of the same dimension and origin as the mat in Figure 4. This overview includes a schematic presentation of the metabolic processes ongoing in such a mat. (W. E. Krumbein, V. Schostak and L. J. Stal, 1986).

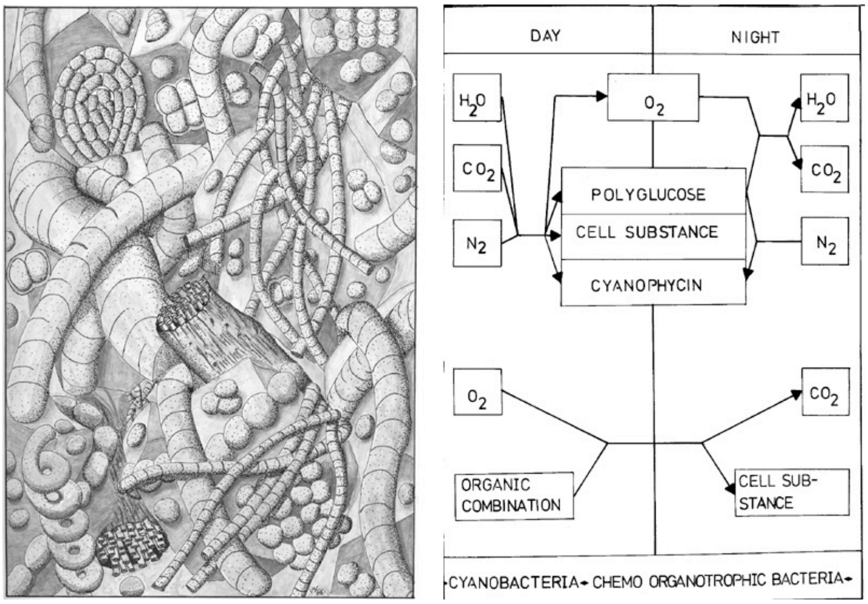

Figure 10: Blow-up of the topmost section of the mat in Figure 9

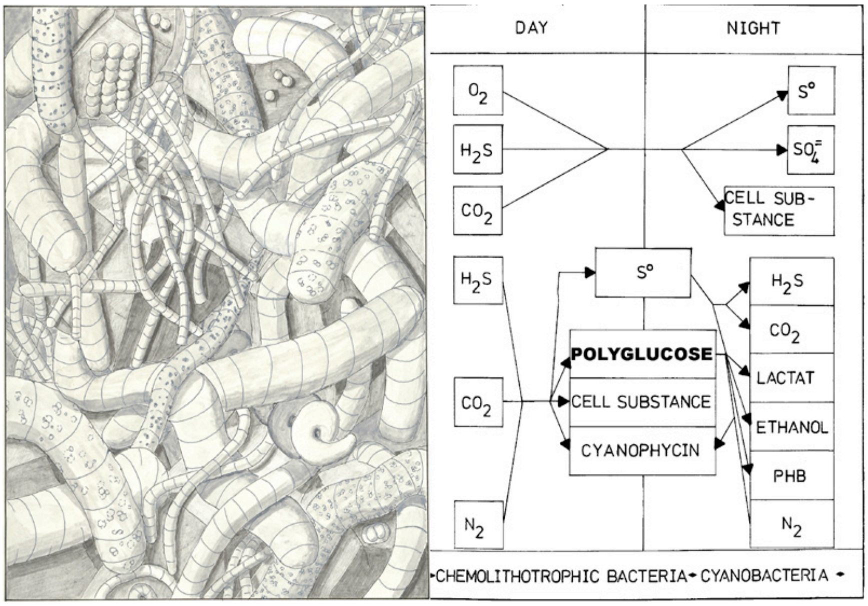

Figure 11: Second layer of the mat in Figure 9.

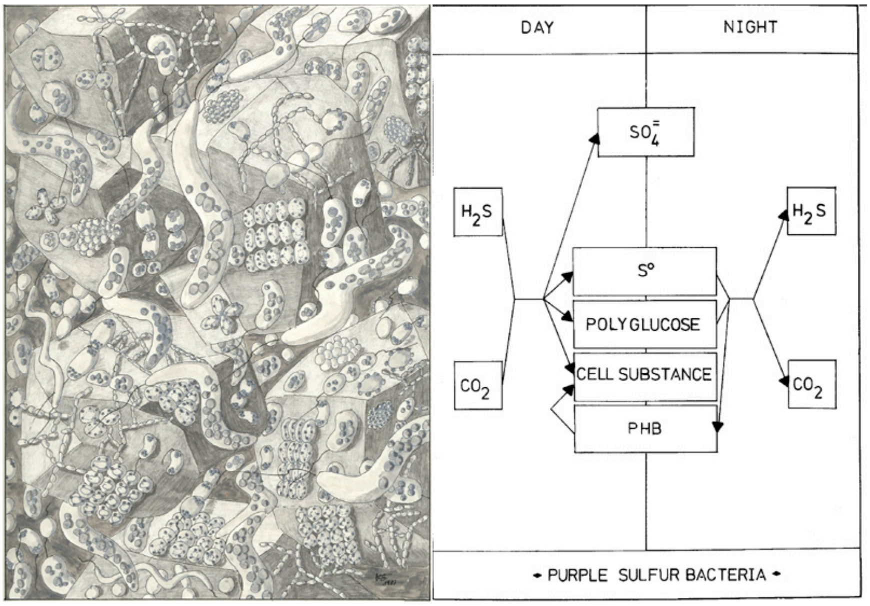

Figure 12: Third layer of the mat in Figure 9.

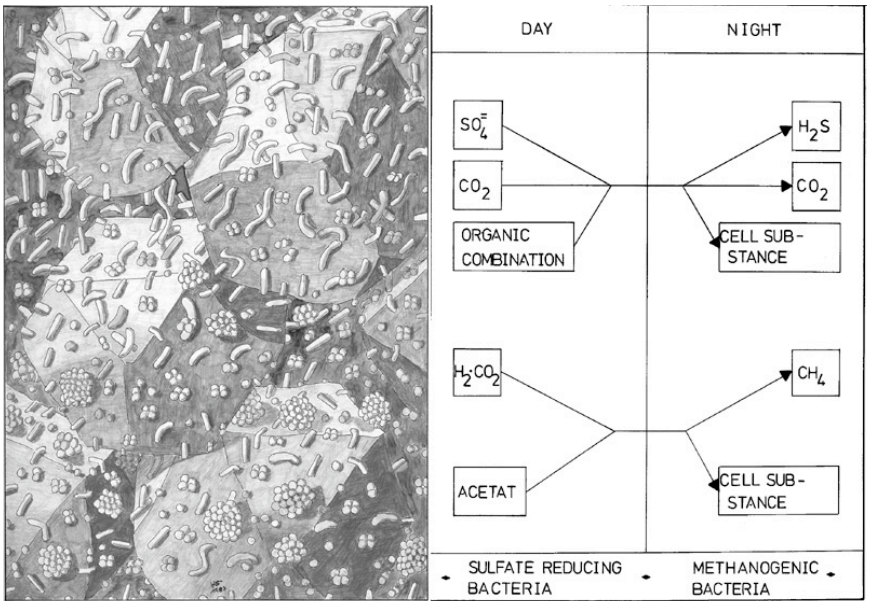

Figure 13: Lowermost layer of the mat in Figure 9.

5. MICROBIALITES (STROMATOLITES, OOLITES, BANDED IRON FORMATION, BIF, LAMINATED ORE DEPOSITS

(Brückmann, 1721, Cloud, 1942; Gerdes and Krumbein, 1987; Kalkowsky, 1908; Krumbein et al. 1994; Riding and Awramik, 2000; Walter, 1976;)

All rocks and rock types, which are visibly generated under the influence of biofilms or microbial mats are microbialites. Work on these structures has evolved over the years and generated many different terms (Gerdes and Krumbein, 1987; Krumbein, 1983a, 1987; Krumbein et al., 1994; Riding and Awramik, 2000; Walter, 1976). Practically all sedimentary rocks and ore deposits are at least microbially modified if not microbially generated as upward oriented growth structures (build-ups) in the sense of bioherms and reefs instead of a concept of physical sedimentation deposited by gravity from a liquid medium. Motivated by the complex structures of microbial mats and networks in shallow and deep Sea environments some authors were also tempted to compare the structural complexity of microbial mats with early attempts of tissue development and tissue-like structures. In discussions with German and Russian paleontologists some of the authors (Brehm, 2001; Gerdes and Krumbein, 1976, Wachendörfer, 1991) expressed the view, that microbial spheres and networks as well as gas and water semi-permeable biofilms and microbial mats by inclosing and trapping not only particles but also anions, cations and molecules with their ballon like and air matrass like morphologies are first steps towards metazoa and other tissue forming organisms. This concept was applied to the Ediacara flora or fauna by Gould (1989) and others. Here a connecting link is opened between histology of individuals, histology of communities and an embracing global or terrestrial parahistology in the sense of Wachendörfer (1991).

Stromatolites are finely laminated sedimentary structures initiated and produced by microbiota by upward directed growth, trapping of and in situ production of mineral particles which include and produce various different forms distinctly of a biogenic origin (Krumbein, 1983a; Noffke et al., 2001; Wachendörfer et al., 1994;). Distinctly bedded, widely extensive, blanket-like build-ups are biostromes. Nodular, biscuit-like, dome-shaped or columnar stromatolites are also referred to as bioherms (Krumbein, 1983a, Krumbein 1984). Benthic films and interwoven structures of cyanobacteria, diatoms and a multitude of other bacteria and eukaryotes (Protozoa) usually represent the modern analogues of these laminated rocks (stromatolites) which are the first extensive biosedimentary rock structures known to exist since the Archean (3.2 – 3.7 GA before present). More and more clearly recognisable forms of filamentous and coccoid or rod shaped cells and cell clusters occur in sedimentary rocks from 3.2 –1.8 GA before present until today. Many important ore deposits such as the iron sulfide and oxide ores, uranium, copper, silver and gold deposits can be mined only because microbial mats enriched the metals within the sediment during their growth period.

6. GEOPHYSIOLOGY, GLOBAL MECHANISM, PARAHISTOLOGY

What is geophysiology? In one of his first books the author of the Gaia hypothesis (Lovelock, 1979, 1989) phrased the idea that if Hutton (1788) talked of Earth as a super-organism and physiology as the method to study Earth stated that physiology was a sub-discipline of medicine and that humankind should be the doctor to treat the problems of the patient Earth (a sick planet). This caused a dispute on the meaning of words in a historical sense. One of the authors of this introductory chapter was biassed into science theory and philosophy in order to analyse the meaning of what Lovelock stated. It turned out, that in a Cartesian sense also a clock is an organism. Worse, physiology at the time of Hutton was defined very different from modern interpretation. We quote from a dictionary of the late 18th Century: “Physiology or Physicks or Natural philosophy is the science of the phenomena and processes of natural bodies”. This means in a nutshell that physicks and physiology were synonyms and that natural bodies could be “living” or “dead organisms”. Derived from this historical excursion we later defined: “If physiology is the science to study the phenomena and processes of natural bodies, then geophysiology can be regarded as the science to study the phenomena and processes of Earth as a living natural body. Hence, biofilms, microbial mats and networks (Biodictyon) will be the major driving elements of the organisation and maintenance of the optimal conditions for the maintenance of Life and Earth through space and time. This is also the view of modern scientists, who revived the thoughts of Aristotle, Albertus Magnus, Giordano Bruno, Paracelsus and others have to be mentioned in this context. (Krumbein, 1983b, 1996).

How then does histology (to say nothing at first about parahistology) get into the picture? Since biofilms and microbial mats can be compared to tissue in structure, cohesion and distribution of tasks of individual cells histological techniques can also be applied. Since histology is the science of plant or animal tissue and Earth cannot be regarded as a real living organism the study of these structures will have to be regarded as parahistology (not to be confused with parapsychology). Actually geophysiology or physiology of the Earth could also be defined as paraphysiology. The latter, however, is nothing else but global or environmental biogeochemistry (Krumbein, 1996).

Recent mass and turnover balances of biological and geochemical cycles make it clear, that the number and mass of micro-organisms as well as their impact on atmosphere, hydrosphere and geosphere can be identified as 99% or more of the total living matter on Earth. Most of the micro-organisms, however, are organized in biofilm or microbial mat communities. This way it can be easily derived, that despite the considerable impact of the human technical system on Earth and the relation of Earth to the Solar system, biofilms still are the major factor regulating the survival of the delicate equilibrium between external influences (Solar irradiation, morphogenesis of the Earth's outer envelope, geochemical cycling of elements in and out Earth and the Earth's Crust) and the home-made response of living (microbial biofilm) systems interacting with the driving forces of the physical (astrophysical) evolution of the solar system within the Milky Way. It seems, that biofilms, microbial mats, and the microbial network (biodyction) deep in the Crust are the major factors maintaining life on this peculiar planetary body, named "Geos" or "Earth". So much about geophysiology. What is then "global mechanism"? Global mechanism or global dynamics is nothing more or less then the geophysiological and global biogeochemical impact of biofilm and microbial mat communities on the major driving forces of the dynamics of Earth as related to the external factors and stresses imposed on it via astrophysical laws and circumstances. Thus if solar irradiation increases or decreases, the living system (and 99.9% of it are represented by biofilms/microbial mats) will have to respond to it with only one means, i.e. maintain life on the planetary body. This planet was by reasons unknown inoculated or infected with a thermodynamic natural system called "Life" by some people and "Dissymmetry" in the sense of Pasteur and Curie by others (Krumbein, 1996; Krumbein and Schellnhuber, 1990, 1992; Levit et al., 1999). What we should never forget or omit from our vain thoughts is the proportion of human cells to microbial cells, of human geochemical activities as compared to the enormous capacity of global microbial (biofilm/microbial mat) activities. In this frame global biogeochemistry, global carbon and other element cycles are without doubt powered by biofilms and microbial mats and networks rather than by human chemical or physical, “pollution”. This way we can feel relatively free to say, that quantity and quality of microbial activities (still) outcompete any activity of macro-organisms including the human ever growing population of a restricted part of the surface of this planet. Planetary biology in the future will teach us to properly understand the biogeochemical difference between humankind and the microbial system.

7. EXAMPLES ON A LOCAL AND GLOBAL SCALE

It is very difficult to find solid surfaces on planet Earth within the range of the highest mountains to the deepest bottoms of the Oceans and within recent sediments and ancient rocks where liquid water is at least sporadically available. The temperature range is between –40°C and + 120°C, especially when the liquid water is under pressure. Biofilm communities, i.e. closely related clusters of micro-organisms attached to a surface and often embedded in EPS thrive not only on rocks, on and in sedimentary granular systems but also in deep rock cracks and interfaces between geological units. The vertical range of these systems spans from 10 km above sea level to more than 20 km below the surface of water the Ocean, and the sediment/water interface beneath. In short: Microbial mats and their products may occur on this planet as a phenomenon of planetary biology at any place offering biologically available water and temperatures below 120°C. This comprises the whole geomorphologic range from approximately 10km above NN to 10km below NN and the crustal range from rock or sediment surface to 20-30km below rock and sedimentary surface level. This includes biofilms and microbial mats or networks exposed to Earth’s atmosphere, hydrosphere and upper geosphere (deep biosphere). Figures 9-13 document this potential of biogeomorphogenetic potential as well as the biogeochemical consequences of the individual morphotypes. Unfortunately the elegant and genial work of the founder of biomorphogenesis as a science (D’Arcy Thompson, 1917) despite the similarly elegant memorizing essays by Ruth D’Arcy Thompson (1958) and E. G. Hutchinson (1948) is somehow lost from extent perception of morphotype analysis. The work of Beklemishev (Levit and Krumbein, 1999) and Viles (1984) have repeatedly attracted attention to the tremendous power of the arrangement of individual micro-organisms and macro-organisms in time and space. Recently it was also demonstrated, that the erosional and accretionary features of karst are intimately associated to microbial films and networks including the fungal associations in the hanging drops of stalactites in formation (Viles, 1984, Wang et al., 1993). Biogeomorphogenesis has a mechanical/physical and a biogeochemical or geophysiological connotation and keeps the chemistry and morphology of Earth far from any thermodynamic, stoichiometric and astrophysical equilibrium or constant. The work of biofilms and microbial mats more than the work of any other community including humankind creates, maintains and shapes the morphology and geochemistry of at least the Earth Crust, including ocean and atmosphere dynamics (water movement, climate) Some glimpses of these ideas have already been coined by I. Kant in a very concise manner (Krumbein, 1993b).

For us it suffices to state: microbial biofilms, microbial mats and microbial networks not only are at the basis of any structure and function of macro-organisms (as witnessed by biofilms microbial mats and networks within and around e. g. trees, termites and humans) but also of the relief of this planet. In this last statement it is tentatively proposed that the deviation of the planetary surface of Earth from the ideal spherical shape as constantly organised by plate tectonics and erosion is at least in part a consequence of the global activity of microbial communities labelled as biofilms, microbial mats or biodictyon.

8. CONCLUSION

Biofilms and especially fully developed mature microbial mats embrace all metabolic pathways ever emerging on Earth. These embrace anoxygenic and oxygenic phototrophy, anaerobic and aerobic chemotrophy, organic and inorganic respiration and fermentation (disproportioning), autotrophy and heterotrophy regarding all nutrients. No element of the forces driving life on Earth is not represented within them since more than 3 billion of years. They are thus ultra-conservative and non-evolutionary. Biofilms and Microbial Mats are evolutionary almost totally stable. They are not a part of Darwinian evolution. Biofilms and/or microbial mats create sediments, sedimentary rocks, island and ore deposits. They destroy rocks, monuments and materials. As a “patina biofilm” they protect rocks and monuments from decay. Fossilised microbial mats are stromatolites, oolites, onkolites and many other rocks and ore or petroleum and gas deposits called microbialites. They serve as energy and matter reservoirs, filters, traps and gradient maintaining systems throughout history of life on Earth. They are even regarded as the fueling or powering systems for global tectonics and climate change or stabilisaton (Anderson, 1984, Krumbein and Schellnhuber, 1990). The biofilm and microbial mat systems (sub-aquatic and sub-aerial) are the true driving forces for the establishment, maintenance and future of life on Earth. They even today in the era of eukaryotes (including humankind) outnumber in importance, mass and turnover rates all other living organisms. More than 99% of the living matter (standing crop) on this planet at least as well as more than 99% of the thermodynamic turnover potential on Earth are represented by biofilms, microbial mats and biodictyons of the deep sub-surface layers of Earth.

ACKNOWLEDGEMENTS

The work on sub-aquatic, sub-aerial and (in part) sub-terrestrial biofilms was generously supported by several grants of DFG and the EU. We are indebted to V. Schostak and L. J. Stal for their participation in creating Figures 5-9. All authors have been involved in the planning and organisation of the Microbial Mat Meetings MMMI and MMMII. All of them wish to express their gratitude to the past and present collaboration with many others working at ICBM on biofilms (G. Gerdes, E. Holtkamp, N. Noffke, H. Riege, L. J. Stal, V. Wachendörfer and others as witnessed by many PhD theses and joint publications with the authors). The co-editors D. M. Paterson And G. A. Zavarzin are acknowledged especially deeply. They would have been excellent partners in the formulation of this introductory chapter. However, limits of time and separation in space made this impossible.

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