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Biogenerated Rock Structures

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Abstract Earth as a planet under firm control of life processes since more than 3 Ga has evolved global biogeochemical cycles, biogeomorphogenetic processes and structures also called plates or global tectonics including global climate and movement of water masses. These processes have deep impact on the shape and thickness of continental land masses as well as the chemistry and mineralogy of the crust and upper mantle. Biogenerated rock structures in this sense can be visualised through the analysis of sedimentary rock structures exhibiting e.g., biogenerated stromatolites, onkolites, oolites or cementing structures of sandstones which clearly preserve biochemical processes and biophysical structures. Further the chemical composition including the segregation of mineral layers, ore deposits, sedimentary and metamorphic rocks and granites hint to sun powered energy storage (gas, gas hydrates, hydrocarbons, coal) and tectonic processes initiated or at least modified through the enormous input of external energy through reduced carbon and iron compounds. One can state with considerable reliability that a planet under control of life must exhibit rock chemistry, mineralogy and structures typical for the impact of life on the geodynamic cycles. This includes the idea of top-down geotectonics instead of bottom-up processes.

Keywords Biogeomorphogenesis · Biogeochemistry · Geotectonics · Oolites · Onkolites · Platonics stromatolites

1 Introduction

Imagine a scenario where intelligent alien life forms, through interstellar travel, approach an unknown planet in search of life. First, they would screen for unusual modulations of the electro-magnetic field, i.e. intelligent background noise or pollution. Second, after determining the planet's composition—gaseous, liquid, or solid—the research team would take a closer look for plant, animal, or other kinds of morphotypes; their analysis would include differentiating between physical and mineralogical products. If the team decides to land—or

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perhaps before landing—they would conduct a more detailed search that might yield living bacteria, micro-algae, fungi or alike.

Let us assume, however, that the planet under examination is dead! No TV, no radio, neither plant nor animal, not even a single living bacterium can be detected with all available techniques.

Will the alien research team now mark the planet as uninhabitable? Rather no. Planets designated uninhabitable may have been habitable in the past or could become habitable in the future, depending on the evolution and circumstances of the star around which the planet revolves. Therefore the team will most probably turn to classical approaches of planetary science (perhaps also to geophysiology). The team will examine rock samples for fossils, petrified traces of ancient life. Let us assume the planet under investigation is Terra in the Solar system. Let us further assume a planetoid or comet impact occurred 3 billion years after Terra's accretion. The impact was so severe, that all established life was abruptly extinguished. Such scenarios are well known as "snow ball" world or "impact" derived extinctions in our own scientific jargon.

The question is: If such an event happened at the end of the Precambrian, or even 700 million years ago, will the research team from afar be able to unravel the planet's life history? Will they find evidence of the biofilm, microbial mats, or the incredible, active photosynthesis cycles and rotations of biologically animated carbon atoms by analyzing the rocks remaining in the planetary crust since the catastrophe? How would this be achieved? Three (or more steps) of investigation would be promising.

- The search for physical fossils (body fossils) in rock materials
- The search for chemical biosignatures in rock materials
- The search for physical (mechanical, structural) biosignatures in rock materials.

In this article we will only briefly touch on the first two possible approaches and focus mainly on the third one, namely physical signatures of unequivocal biologically generated structures, morphologies, or minerals. Last but not least, global structures or platonics will be discussed as unequivocal signs of former or extant life. This will be derived from the ratio of reduced and oxidized compounds in the solid crust of the planet as well as from the resulting morphology.

2 Fossils

The geological and paleontological literature is full of attempts to identify and to describe microorganisms in ancient sediments. Many of the structures described and published turned out to be artifacts, erroneous outcome of microscopy and misinterpretation of simple morphologies. The same is true for the multitude of reports on bacteria or other structures detected in meteorites of Martian origin or from farther away. Actually, one can cast doubt on many fossils reported for the first two billion years of life on Earth.

3 Chemical Signatures

Following the old idea of dissymmetry—forwarded by Pasteur and Curie and fully developed by Jasper and Vernadsky in the last decade of the nineteenth and first decades of the twentieth centuries (Levit et al. 1999)—many researchers have looked into the dissymmetry of stable isotopes, especially those of a high biological migration potential, namely carbon, sulphur, and oxygen (van Zuilen 2007; Ono 2007). During metabolic activity, these isotopes are fractionated frequently in a way that deviates from normal physical–chemical conditions. Often the lighter isotope is enriched in cell material. This enrichment may be preserved in the dead cell material or organic compounds derived from living systems. Many if not all these signatures, however, have turned out to be ambiguous and could be explained by special climatic conditions or other processes not related to life. Thus, it turned out to be useful to study structures and physical conditions in addition to the search for fossil microbes and their isotope-fractionating activities.

4 Biogenerated Rock Signatures

Physical or physical–chemical signatures of life are multiple and absolutely convincing in the case of macroorganisms. Some classical examples are the depression and—at a certain distance—the pile of spaghetti-like excretions produced by *Arenicola marina* or the worm-like tubes of *Rhizocorallium.* Many other examples from the macroscopic end of the mesoscopic physical world could be given. One of the truly enigmatic biosignatures is the *Microcodium* complex in fossil soils. Another very debated set of biosignatures visible to the naked eye are the root and fungal network signatures in agate samples (coloured and banded silica or chert concretions sold in many mineral shops all over the world). The biological remains are repeatedly embedded in cavities in relatively cool silica exhalations.

However, in our initial scenario, life on Earth was abruptly extinguished before multicellular organisms established themselves. Therefore the exploration team must turn to more hidden and cryptic structures and signatures.

5 Microbial Growth Structures (Including Kerogen and Carbonate Deposits)

The first reports on such structures apparently, and most astonishingly, are based on observations from the Germanic Trias around the Hercynian Mountains in the centre of Germany. The wandering scholar and Medicus Philipp von Hohenheimb, who named himself Paracelsus (around 1548), reported some interesting structures in a clear mountain creek. He saw a slime forming on some granite pebbles and concluded that this slime transformed into calcium carbonate, cementing the pebbles. He even confirmed his field observations by laboratory experiments in cucurbites (Erlenmeyer flask-like vessels). Thus, under his eyes, biological activity transformed loose pebbles into a carbonate-cemented conglomerate. Many generations of geoscientists, however, claimed that living matter was not necessary to produce such rock structures. Some years later another Medicus (Brueckmann 1721) described some concentric structures previously known as roe stones or frog eggs; these were also depicted by Hooke (1665) as “Kettering stone”. Brueckmann first named them oolites and regarded them as made ex vivo. It took another 125 years until Ludwig and Theobald (1852) described the formation of these oolite grains within algal carpets in the thermal waters of Bad Nauheim and demonstrated that the grains, which formed in the algal carpet, were washed away and redeposited downriver upon the decay and elimination of the algal cell material. Kalkowsky (1908) visited the same localities in the Harz Mountains and named for the first time the whole ensemble of these biosedimentary structures. He described very precisely what he called stromatolites (rocks made of individual stromatoids) and oolites (rocks made of individual ooids and ooid bags). Following Ludwig and Theobald (1852), he attributed all these very conspicuous and characteristic sedimentary rock structures to microorganisms.

Fig. 1 A sandy beach transforms in beachrock (*upper left*) and stromatolite and onkolite (*lower part*)

From then on research on stromatolites and stromatolitic structures, ooids and oolithic structures expanded tremendously. However, especially for ooids and oolites, the discussion went on whether or not biological processes play a role in the formation of these characteristic structures. There is now almost general agreement, however, about the statement of Carl von Linné that the petrifacts in carbonate rocks are not generated in the rock. On the contrary, the carbonate rocks have been generated by the organisms found within them ("omnis calx ex vivo"). Today we know that microorganisms, instead of the embedded macrofossils and their carbonate skeletons, generate most carbonate rocks on earth.

An elegant experimental approach was described by Brehm et al. (2003). They convincingly showed that a complex community of one cyanobacterial species, one diatom species and about a dozen species of heterotroph bacteria organise themselves in a special way to produce at first organic spheres, which later are filled with diatoms and cyanobacteria, subsequently calcifying into ooids. This community is very specific and well organised. Bacteria arrange themselves in spheres, form an organic coated balloon filled with water and surrounded by water, not unlike the macroscopic cyanobacterial spheres of Mares Egg (Oregon) and some Karelian lakes (Russia). These, however, have never been described as calcifying. Thus Paracelsus (1976), Brueckmann (1721), Ludwig and Theobald (1852), and last but not least Kalkowsky (1908) have laid the foundation for the detection, study and char-

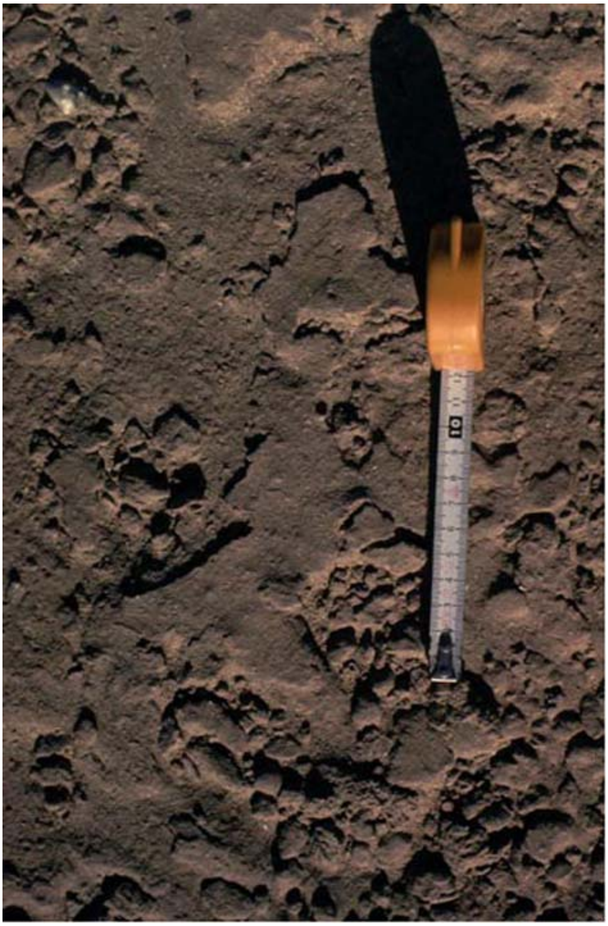

Fig. 2 Step one: mat formation and disintegration according to nutrient and pore water supply

acterisation of biosedimentary signatures derived from subaquatic biofilms or stromatolitic microbial mats with their astonishing individual morphologies, which as a whole can only be produced by living organisms. The structures, however, usually contain no traces of organisms and one individual lamina (stromatoid) of any stromatolite may represent 100 years of microbial mat formation in annual cycles of production and decay (Krumbein et al. 1977; Walter 1976). The controversial discussion on ooids and oolites need not be repeated here. The literature is vast (Dahanayake et al. 1985). One example of in situ formation of biosedimentary structures is given from the coast of the Gulf of Aqaba (Figs. 1, 2, 3 and 4).

6 What then Is Important for Our Alien Planet Exploration Team?

Usually biogenic stromatolites and biogenic oolites (still questioned by many authors according to origin or place of formation—biogenic/abiogenic? planktonic/benthonic?) are described from limestone environments. Many siliciclastic structures, however, have been described as well (Figs. 5, 6 and 7).

Fig. 3 Sand dollar like structures emerge and stabilise thin layers of sand in irregular patterns

Examples of ferruginous or phosphatic stromatolites and oolites also exist (Dahanayake and Krumbein 1986); many stromatolite-like structures may be abiogenic as well (Krumbein 1983).

Stromatolites and oolites are usually attributed to cyanobacteria. However, many stromatolites have been identified as being generated by fungi or filamentous nonphotosynthetic bacteria (Krumbein 1983; Gerdes and Krumbein 1987). In exceptional cases, stromaolitic structures also emerge from macroorganisms (Krumbein, 1963, 1983).

Furthermore, the study of recent microbial mats focuses too much on the organisms themselves and less on their envelopes, often called extracellular polymeric substances (EPS). As a matter of fact, EPS are more resistant to decay then the organisms embedded in them. The mechanical stability of EPS is astonishing, comparable to spider web material in the sense that it remains unmatched by any synthetic product.

Finally there is a lack of detailed comparative studies of the contrast between sedimentary rock structures, derived from transport of grains and deposition, and the completely different situation of "Aufwuchs" structures. This term defines the growth of sedimentary rocks from "bottom up" instead of from "top down". Thus, in reality, many sedimentary rocks are not really sediments. They represent biological growth, into which grains are incidentally embedded and captured. Such structures differ considerably from

Fig. 4 Upon anaerobic total decay of the cyanobacteria biofilm, Onkolites calcify

a sedimentation; i.e., a purely physical deposition by gravity (Wachendörfer et al. 1994a, 1994b). In Fig. 6, dark angular quartz grains are floating freely within the extracellular polymeric substances (EPS) produced by a complex microbial community. The EPS were produced in excess amounts for many physiological and ecological reasons. These substances are more rigid and pressure resistant than many minerals, and possess porosities or special cementing minerals that may be generated only in very late stages of sedimentary diagenesis (sometimes only when heated above 100°C and after undergoing some Maillard reaction transformations). Thus very peculiar rock structures are formed in carbonates and sandstones; these, in turn, are regarded as signals of biological growth even when totally transformed into granites. Vernadsky (1929), and more recently many others (Arp et al. 2001; Anderson, 1984, 2006; Krumbein, 1983, 1996; Krumbein et al. 2006; Rosing et al. 2006) discussed these views of a biologically structured crust model.

The most ancient documents of life on Earth are, apparently, the biosedimentary impacts and traces of biofilms or microbial mats. A biofilm, if subaquatic, can be regarded as 99% solid water stabilised and immobilised by large amounts of extracellular compounds (EPS) excreted by few microorganisms (bacteria, cyanobacteria, algae, or fungi). These films could really be called a tissue and exhibit even more specialized structures than animal or plant tissue studied in much more detail (e.g., Walter 1976; Brehm et al. 2006).

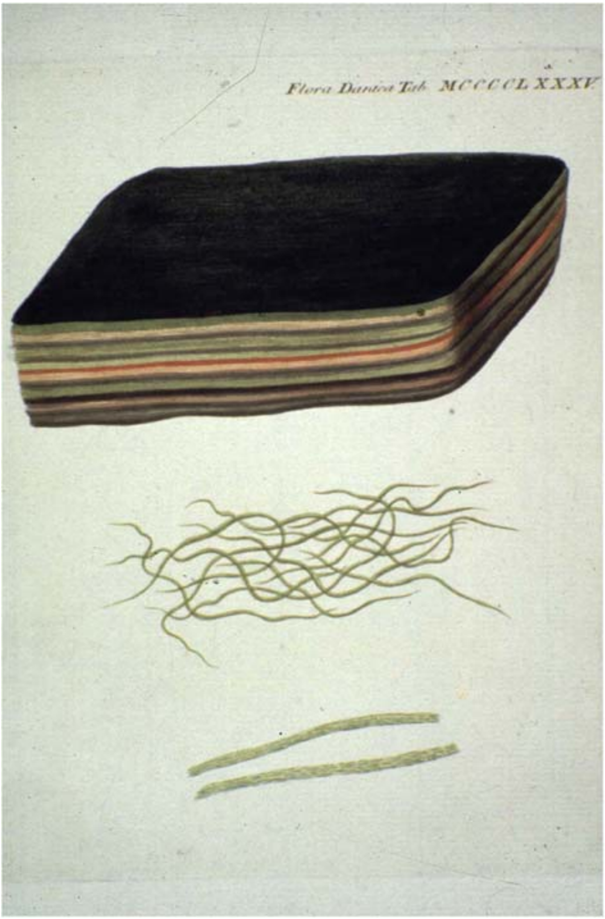

Fig. 5 First demonstration of a biofilm generated sedimentary structure (*Flora Danica*, 1813)

In contrast, a subaerial biofilm can be regarded as highly structured 99% cellular or extracellular material (EPS) surviving and spreading with a minimum supply of water. Dark zones in, e.g., Fig. 8 are spaces not calcified because EPS was characteristically not calcifying in this part of the tissue-like build-up of the cyanobacterium *Scytonema* which forms in the irregular (sporadic) intertidal areas of alpine lakes.

Both types of biofilms and, in addition, microbial networks (biodictyon) within rocks and rock cavities may produce minerals and morphological patterns that differ considerably from purely physically produced structures and morphotypes (Fig. 8). The morphological and topological difference between a physical deposit (varvite) and a biosedimentary deposit (stromatolite) is often difficult to trace. Some authors suggested the term “stromatoloid” when typically laminated structures are observed without unequivocal evidence of microbiota as a source. Furthermore, biofilm-generated ooids and oolites, onkoids and onkolites were described and could also be assigned different names, which would then clearly indicate the biogenic or physical origin of the morphotype in question.

When regarding fossil and present-day biospheres, it is astonishing that for more than 80% of the existence of life on Earth (3.7 Ga) these communities were thriving in a biosphere stabilised for Eons. Only 0.5 Ga ago, complex communities of macroorganisms emerged and associated symbiotically with biofilms to form grasslands, trees, and forests or coral reefs to

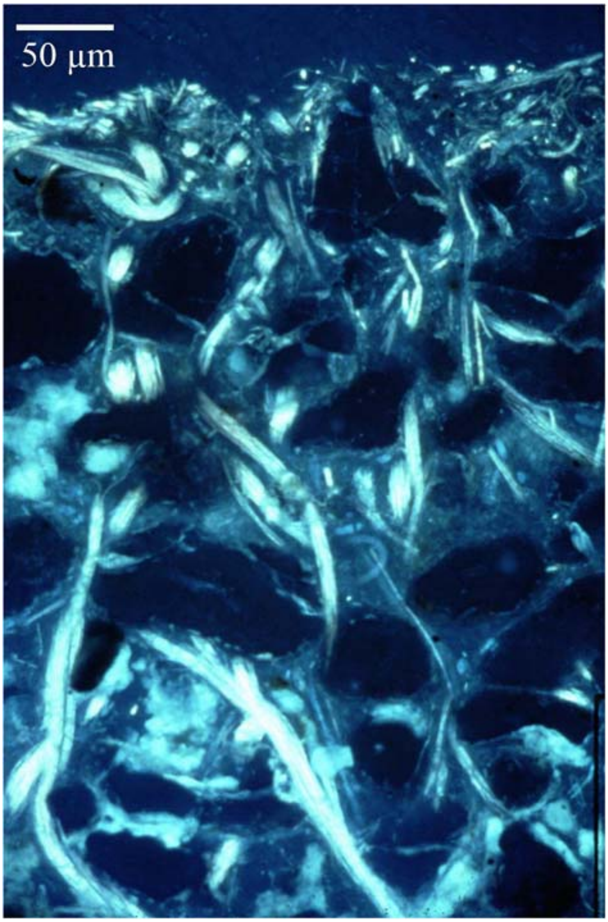

Fig. 6 Sand grains without any contact will get fossilised swimming in carbonate cement

name a few examples of these symbiotic mesoscopic success stories. Naturally, this would include rocks or former soils enclosing remains of Coca-Cola bottles.

Subaquatic, subterranean (rock inherent), and subaerial biofilms need to be considered separately. In a global sense biofilms can be regarded as a kind of a super tissue, and parahistology could be applied to these peculiar structures (Levit et al. 1999; Wachendörfer et al. 1994b). The terms biofilm, microbial mat and stromatolite—which describe complex multilayered biofilms creating, designating, and destroying rocks—were only coined in the twentieth century. The first scientific descriptions of such communities and their rock-creating potential stem from the *Flora Danica*, initiated in 1761 by G.C. Oeder. The first polychrome picture of a microbial mat or stromatolite was published in 1813 in issue 25 of the *Flora Danica* (Fig. 5). *Oscillatoria,* and later more correctly *Microcoleus chthonoplastes,* was named soil and rock forming because it was observed that leathery biofilms created by this microorganism could build islands that rose above sea level; not unlike coral reefs built by atoll islands in tropical seas. Considering the evolution of biosedimentology, it is worthwhile to note that studies on stromatolitic structures were reported almost 50 years before Ehrenberg and Darwin published their monographs on coral reef growth as a source of biosedimentary rock structures.

Fig. 7 Balls of silt and clay are formed by biofilm growth. No microbes left in internal structure

Geosciences unfortunately concentrated on macroorganisms in terms of sedimentology and stratigraphy for more than 150 years. The early work of the Danish (Odense) group, of Ehrenberg (1854) and of Kalkowsky (1908) remained unnoticed until Krumbein (1983), Walter (1976), and others attracted attention to biosedimentary rocks made by biofilms. Consequently, the notion of benthic Oolites, onkolites and stromatolites being constructed by the same microbiota and stromatolitic biofilms was studied and acknowledged. Mud cracks, table cloth folding, Tepee structures were matched with their biosedimentary counterparts such as Petee, Elephant skin and complex biolaminated negative or positive cones and stylolites (Friedman and Krumbein 1985; Gerdes and Krumbein 1987; Krumbein et al. 2004).

Microbial-induced sedimentary structures (MISS) were introduced into the literature by N. Noffke, a student of Seilacher, Gerdes and Krumbein (Noffke et al. 2001). The pattern of structures and individual morphotypes were more clearly defined and made visible in recent and ancient sedimentary systems. Terminology, nomenclature and the history of research into biofilms were sketched out more precisely. Special attention should be given, however, to typical patterns and morphological characteristics, which may enable a clear distinction between purely physical structures and structures that stem from microbially

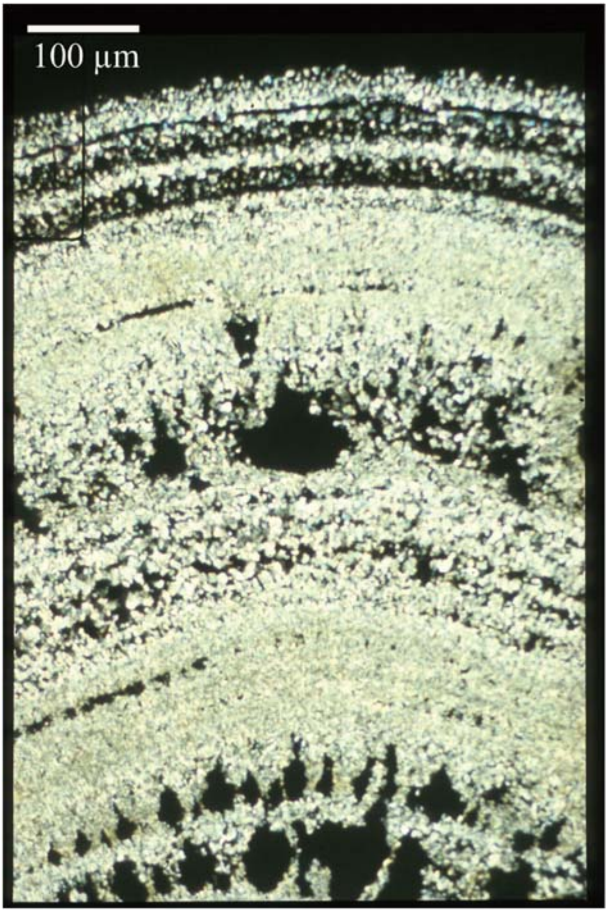

Fig. 8 Laminated structure created by *Rivularia* (Attersee, Austria) lacking fossil microbes

induced sedimentary structures (MISS) and microbially altered rock surfaces (MARS). Both MISS and MARS may be measured using different approaches and then transformed into search algorithms for the detection of ancient and extant biogenic rock formation and rock destruction patterns on a purely mathematical measurement base (Kempe et al. 2005; Rodenacker et al. 2003).

7 Global Biogenic Structures and Processes

We now return to the alien exploration team. The team went to a new solar system immediately after a first glance at the albedo, the cloud systems in the atmosphere and some glances at the distribution of land and water. Naturally they are more advanced in recognizing the impact of living matter than, say, Lomonosov, Kant, Herder or Vernadsky (to name a few). Thus, the team derived from atmosphere composition, cloud pattern, oceanic currents and the size and distribution of land masses, that the planet was transformed by living matter. The report for the books and the mother planet thus could have been:

> The third planet of a small yellow star in galaxy WEK3.14.37 is (or was) controlled and organised by life processes. Living matter exists (existed) in sufficient amounts

to stabilise planet surface temperature and conditions. The migration of atoms under control of living matter embraces approximately 7% of the planetary mass. Unfortunately, the migration of atoms and structural evolution of morphologies stagnated at a level exhibiting lack of intelligent "noosphere" type developments. Life support is (was) good. However, control of the moon and orbiting around the sun, as well as organised use of the solar energy source are (were) rudimentary and changes in this situation seem improbable (are impossible). On the other hand, the turnover of large amounts of mineral and rock in well-equilibrated mixtures of aqueous and solid portions of the surface layers via carbon-based living matter is well documented. The manipulation of large portions of the crust and water masses exists, but is (was) not selective and flexible enough to guarantee long-term survival. The planet may lose (lost) and is thus not eligible for the list of living planets. We suggest the category habitable.

8 Summary

Platonics, i.e. the biologically controlled organisation of large masses of solid matter in a "top down" geotectonic way powered by sun energy (Anderson 1984, 2006; Krumbein 1983; Krumbein et al. 2006; Krumbein and Schellnhuber, 1990, 1992; Rosing et al. 2006) are an outcome of biological migration of atoms through living matter. These processes are powered by external (sun) energy in a top down way, feeding chemical and physical (mechanical and morphological) differences into the upper 7–10% of the planet in order to guarantee energy, nutrient and temperature equilibrium in a global biogeomorphological sense. This combined with the action of living matter guarantees an extension of the window of life on planet Earth and its continued habitability. This way biosedimentary structures extend into global bio-platonic morphologies, which can be analysed as biologically driven processes and patterns from long-distance mapping of the planet's surface. Platonics was derived by Anderson (2006) from plates, tectonics and perhaps even from cratons, all three representing ambiguous terms of present-day Earth system science. The complex composition and evolution (physically and chemically) of large land masses erroneously, termed plates, as contrasted with huge bodies of water and their conveyor functions of temperature and nutrients cannot be explained by simple mechanic functions (implied by the words "plate" or "plate tectonics"). All sediments and sedimentary structures of planets bearing life will be characteristically modified and altered by the impact of living matter. The vertical and horizontal movements and turnover processes of huge amounts of minerals and rocks in life-dependent cycles of geological time dimensions could be called the "breath of Earth", or could be compared to a body with bones, tissue, vessels and nerves as a metaphor to describe the living Earth. Such descriptions were very popular from the Renaissance until the Enlightenment (sixteenth to eighteenth centuries). These cyclic and sometimes cataclysmic changes driven by living matter are detectable from far in space. The migration of atoms, ions and minerals in space and time via living matter involves the uppermost 80–130 km of the planet or 7–10% of its mass. Geophysiology is a more living description for biosignatures on sediments and continents and their fate in space and time then the presently broadly used term earth system science (Krumbein, 1983, 1993b, 1990, 1996).

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