Kalkowsky's Stromatolites and Oolites (Lower Buntsandstein, Northern Germany)

Josef Paul, Tadeusz M. Peryt, and Robert V. Burne

1 Introduction

Three world-wide used geological terms derived from the area around the German Harz Mountains: "Oolithi" (Brückmann 1721) and nearly 200 years later "Ooid" and "Stromatolith" (Kalkowsky 1908). All these three terms deal with carbonate grains and rocks of the Lower Triassic Buntsandstein Group around the Harz Mts. Therefore, this area is in a way the type area of stromatolites. But Kalkowsky did not only coin the name, but also deciphered their microbial origin. Therefore, it may be of interest to have a nearer look at these stromatolites, oolites and the environment in which they grew and to compare Kalkowsky's 100 years old observations and interpretations with recent ones.

2 Studied Area and Stratigraphic Frame

The lithostratigraphic unit hosting Kalkowsky's stromatolites is the Lower Buntsandstein Subgroup which is of Lower Triassic age and time-equivalent to the Induan and lower Olenekian of the International Chronostratigraphic Standard (Table 1). In the studied area, the Lower Buntsandstein Group is about 250 m

J. Paul (✉)
Geoscience Centre, University of Göttingen, Sedimentology Division, Goldschmidtstraße 3, 37077 Göttingen, Germany
e-mail: jpaul@gwdg.de

T.M. Peryt
Polish Geological Institute – National Research Institute, ul. Rakowiecka 4, 00-975 Warszawa, Poland

R.V. Burne
Research School of Earth Sciences, The Australian National University, Canberra, ACT, Australia

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Table 1 Stratigraphic scheme of the Lower Triassic in Germany

Ma: 245, 246, 247, 248, 249, 250, 251

Chronostratigraphy		Lithostratigraphy: Subgroup	Lithostratigraphy: Formation
Anisian	Aegean	Upper Buntsandstein	
Olenekian	Spathian	Middle Buntsandstein	
Olenekian	Smithian	Lower Buntsandstein	Bernburg
Induan	Dienerian	Lower Buntsandstein	Calvörde
Induan	Griesbachian	Lower Buntsandstein	Calvörde
Permian		Zechstein	Fulda

thick and consists of sandstones, mudstones and oolites. It is divided into two formations, the lower Calvörde Fm. and the upper Bernburg Fm. These sediments are organized in about 20 fining upward cycles starting with cross bedded sandstones, followed by oolites and gray mudstones. The cycle is terminated by structureless red mudstones containing small anhydrite nodules. The about 100 m thick Bernburg Fm. contains stromatolites and has more or less the same composition as the underlying Calvörde Fm. Only the percentage of oolites is higher and the Calvörde Fm. contains no stromatolites.

The Buntsandstein Group was deposited in the Central European Basin which was called the Germanic Basin in the past. It was an inland basin with only restricted access to the ocean (Fig. 1). The fining upward cycles are traceable from the Netherlands to Poland and can be used as markers (Geluk and Roehling 1997; Becker 2005). The common occurrence of oolite beds indicates the centre of the basin in contrast to the siliciclastic margins. An individual oolite bed may

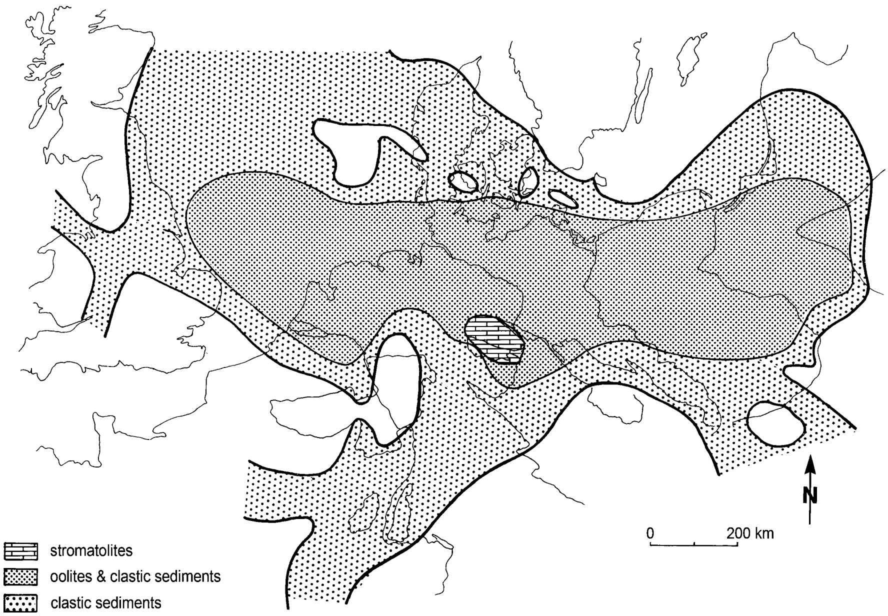

Fig. 1 The Lower Buntsandstein of the Central European Basin. After Paul (1982)

wedge out in some distance, but a series of oolite beds can be traced over some 100 km.

The stromatolites of the Bernburg Fm. are restricted to a relatively small area around the Harz Mts., the Eichsfeld Palaeohigh, which was situated between the Hessian Depression in the west and the Thuringian Subbasin in the east (Fig. 1). It persisted from the Permian until the end of the Triassic. Reduced thicknesses and condensed sequences are characteristic for this palaeohigh. Here, stromatolites are found quite frequently in quarries, road-sections and drilled cores (Dorn 1953; Paul and Klarr 1988; Paul and Peryt 2000). Investigations of Lower Buntsandstein oolites in various wells in other areas of Lower Saxony ended so far without success in finding stromatolites or even stromatolitic crusts.

3 Stromatolites

Ernst Kalkowsky (1908) described stocks or heads of layered or laminated carbonates in oolite beds of the Lower Buntsandstein in the Harz Mountains and defined them in this way (Kalkowsky 1908, p. 68, § 3):

> The new term "Stromatolite" is proposed for limestones with unique organisation and structures that occur associated with "roe-stone" (oolites).
>
> Stromatolites have a fine, more or less even layered fabric that contrasts with the concentric fabric of oolite grains.

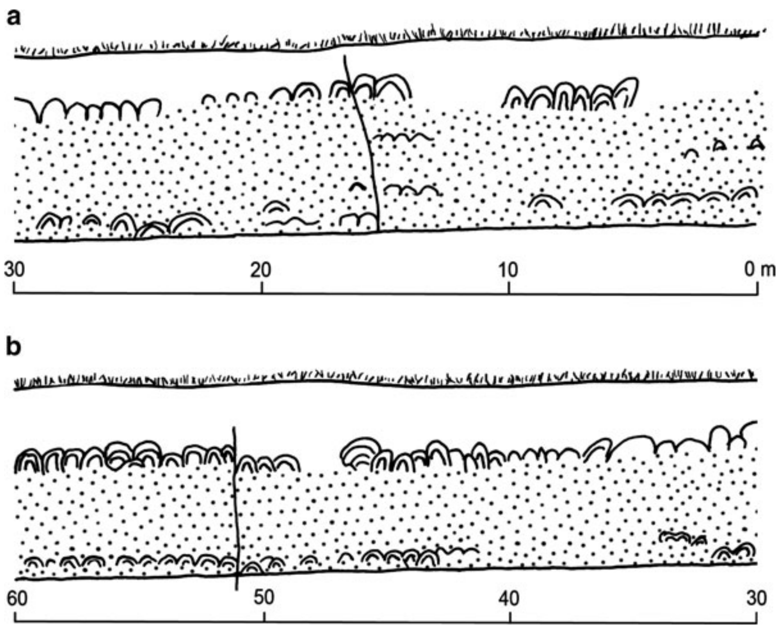

Fig. 2 (**a**, **b**) Oolites and stromatolites at a disused quarry at the Heeseberg

This even layered fabric, the lamination, is according to Kalkowsky (1908) the distinguishing main mark of stromatolites.

Stromatolites are always associated with to oolites. In most cases, they occur at the surface of oolite beds terminating the sedimentation of ooids. The thicker the oolite bed, the higher the probability of occurrence of stromatolites and the larger the stromatolites are. In Heeseberg in an abandoned quarry, a section of 7 m thick oolite beds with stromatolites is exposed for a length of more than 100 m (Figs. 2 and 3). At this 700 m^2 large outcrop, there are nearly no mud layers which normally occupy more than half of the Buntsandstein succession. Stromatolites are not randomly distributed, but occur preferentially in two horizons (Fig. 2). These succession of various types of ooids and stromatolites can be traced a distance of about 1 km.

3.1 Macroscopic Observations

Stromatolites occur as thin, some millimetres thick crusts or as up to 2 m high compound domes or smaller columnar forms (Figs. 4–7). Alternations of thin stromatolitic crusts and oolite layers are quite common (Fig. 8). The largest domes are at the centre of the occurrence of stromatolites. Towards the margins, their size and number decrease. Thin laminated encrustations veneer oolite beds. In some cases, encrustations outline ripples consisting of ooids and make them

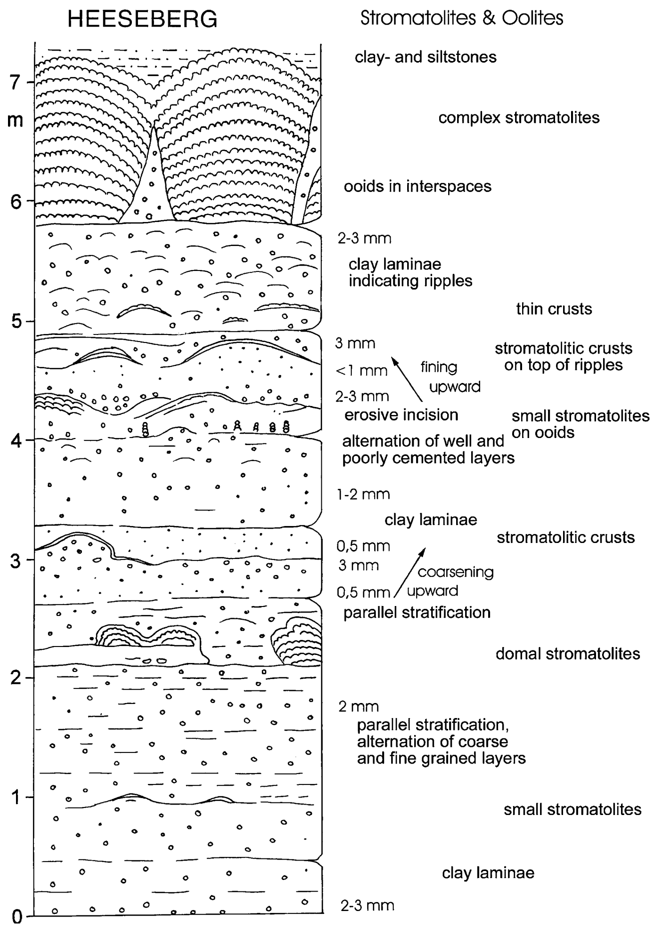

Fig. 3 Section of the oolite bed and domal stromatolites at the Heeseberg. After Paul and Peryt (2000)

visible. Crusts are thick on top of the ripple-crests and wedge out towards the troughs (Fig. 3). In some places, thin isolated columns of some millimetres diameter rise above individual ooids (Fig. 9). Columnar forms may be closed or wide spaced (Figs. 6 and 7). The most frequent stromatolitic forms are domes of various sizes. The larger domes are compound structures consisting of even or inclined layers and up to some cm high columnar forms branching like trees (Fig. 4). Ooids are in the interstices between the branches, but also sometimes incorporated into the stromatolitic tissue. Most likely, the height of the domes was only some centimeters above the sediment surface. Occasionally, the top of stromatolites domes as well as columnar forms is characterized by dissolved and etched surfaces. The size of columns varies between some centimetres and some millimetres (Figs. 4, 6 and 7). Thin stromatolitic crusts occur above oolites (Fig. 8). Very rare is a type of

Fig. 4 Compound domal stromatolite. Scale bar: 10 cm. Salzgitter

Fig. 5 Top view at small columnar stromatolitic crusts. Scale bar: 5 cm. Eisleben

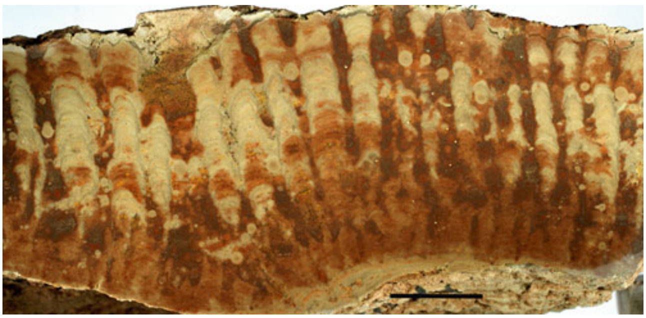

Fig. 6 Close spaced columnar stromatolite. Scale bar: 2 cm. Salzgitter

Fig. 7 Alternation of wide spaced columns and stromatolitic crusts. At the centre shells, most likely of conchostracans. Scale bar: 5 cm. Eisleben

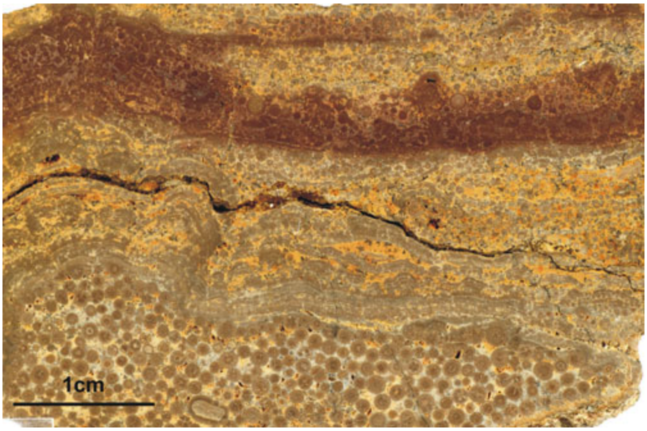

Fig. 8 Thin stromatolitic crust above an uneven surface of an oolite layer. Scale bar: 1 cm. Eisleben

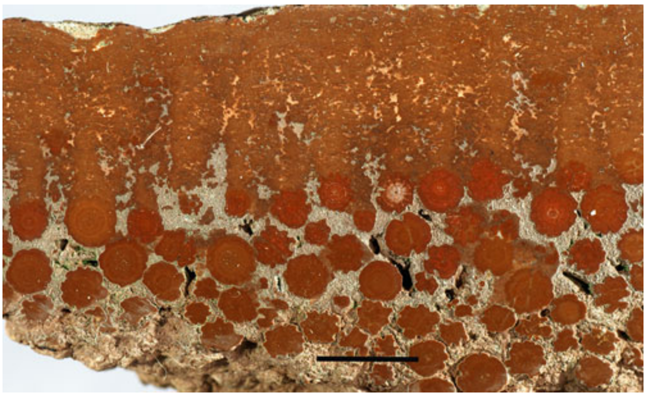

Fig. 9 Small columnar stromatolites growing above single ooids. Scale: 1 cm. Salzgitter

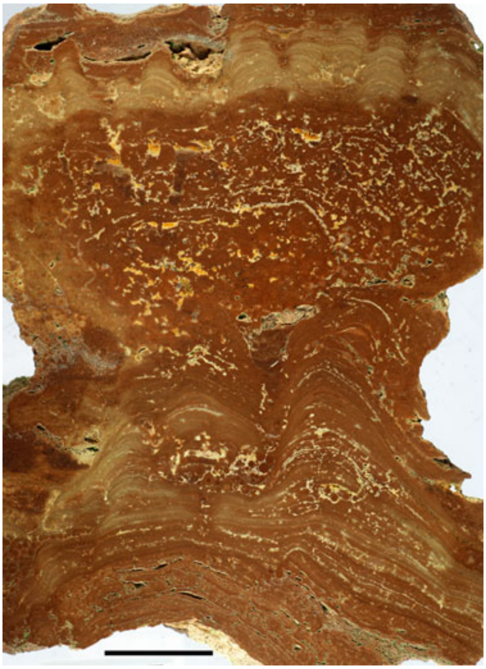

Fig. 10 Closely laminated stromatolitic crusts at the bottom and the top, thrombolite-like structures in the centre. Scale bar: 2 cm. Heeseberg

lamination resembling thrombolitic structure (Fig. 10). Smaller stromatolitic structures and ooids are red in colour due to an admixture (some percent) of haematite which is diagenetically incorporated into the calcite (Scherer 1975).

3.2 Microscopic Observations

The carbonates of the Bernburg Fm. underwent intense diagenetic alterations which destroyed the original tissues. In particular organic compounds have been extinguished by oxidizing conditions which dominated early and late diagenetic processes. Therefore, it is not possible to prove directly the microbial origin of Kalkowsky's stromatolites. But the autophototrophic growth forms on top of ripples, for instance, support this assumption (Fig. 7). Two types of stromatolitic microstructure can be distinguished, a spongy fenestrate and a fan-like which occasionally is a radial-filament (Paul and Peryt 2000) (Fig. 11).

Kalkowsky (1908) distinguished between stromatoids and stromatolites. There have been considerable discussions on what Kalkowsky meant by the term "stromatoid" (Hofmann 1973; Monty 1977; Krumbein 1983). In Kalkowsky's words (1908, p. 65):

> Oolites are composed of ooids and the cement that lithifies them. Stromatolites are composed of thin, more or less flat laminae of calcite with a specific texture. These thin

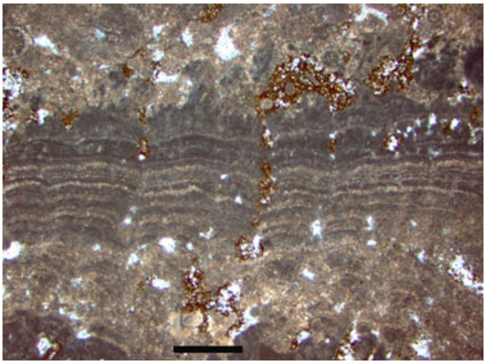

Fig. 11 Stromatolite layer. Thin laminated crusts within the oolites and at the base of stromatolites are formed by radial calcite crystals, whereas columnar stromatolites have spongy-fenestrate fabric Scale bar: 1 mm

> laminae are termed "Stromatoids". Stromatolites, unlike oolites, are not formed by limited individual colonies of constructing organisms; rather layers or mats of constructing organisms form them. There is a trend from ooid through poly-ooid and ooid bag to stromatolite in which the accreting layers show decreasing influence of a central nucleus in determining the form of growth.

From this it is clear that Kalkowsky considered ooids being produced by the growth of limited individual microbial colonies around a nucleus, and that the lithified accumulation of ooids together with the binding cement constitutes an "Oolite". By comparison he considered the individual colonies of microbes grown as non-nucleated layers producing a thin flat lamina of calcite which he termed "Stromatoid", and that the accumulation of cemented laminae, or "Stromatoids", together with their lithifying cements constitutes a "Stromatolite".

He therefore regarded "Ooids" and "Stromatoids" as end members of a continuum, with "poly-ooids" and "Ooid bags" as intermediate stages. However there is a hierarchical shortcoming to this concept in that ooids are individual sediment grains and an oolite is a lithology. A Stromatoid is often composed of grains (some of which may be ooids), and a Stromatolite is a structure within a lithology, though individual Stromatolites may coalesce together to form a lithology. Stromatoid in this sense is thin laminated organic material.

4 Oolites

The 100 m thick Bernburg Fm. at the Eichsfeld Palaeohigh contains up to 20% of oolites. They were investigated petrographically in detail by Usdowski (1962) and Richter (1983). Their sedimentology is worked out by Paul and Peryt (2000) and Palermo et al. (2008). In the centre of the Eichsfeld Palaeohigh, oolite beds are up to 7 m thick and ooids can reach a size of up to 10 mm, but usually they are between 0.2 and 3.5 mm in diameter (Figs. 12 and 13). Ooid size and thickness of the oolite beds decrease with increasing distance from the palaeohighs. Normally,

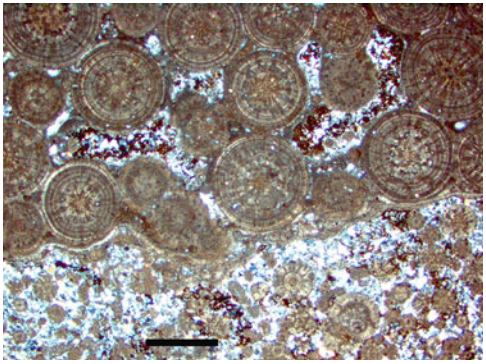

Fig 12 Well sorted ooids with a thin stromatolitic crust. Scale bar: 1 mm. Heeseberg

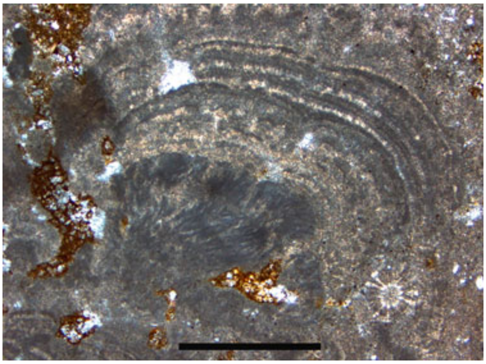

Fig. 13 Stromatolitic tissue with microbial tubes, most likely cyanobacterial sheaths. Scale bar: 1 mm. Heeseberg

the ooids consist of calcite and have a core of small quartz or mica grain or a calcite crystal. Richter (1983) assumed that the ooids originally consisted of magnesium calcite.

Under the microscope, there are two types of ooids recognizable. The majority of ooids consists of thin concentric layers of calcite and the other type has fine, radially oriented calcite fibres (Usdowski 1962). Both types are found side by side and can merge into each other. Often, the cores are more radially oriented, whereas the outer layers are still intact. This phenomen is independent of grain size or other parameters like position in the oolite bed. According to Scherer (1975), the ooids have an iron content of some percent. This is a clear indication of late diagenetic recrystallization during burial. Occasionally, ooids are meshed as consequence of pressure solution. Two or even more ooids are merged, which means that they have common outer layers. Clasts of ooids are wrapped up by thin stromatolitic layers (Fig. 14).

The 7 m thick oolite bed of the above mentioned outcrop at the Heeseberg consists of amalgamated oolite sheets. Careful examination indicated that most of the dm-thick oolite beds can be traced all over the outcrop. There are only very

Fig. 14 Ooid intraclasts coated with thin stromatolitic crust. Scale bar: 5 cm. Salzgitter-Osterlinde

few erosional features like channels or cross-bedding. The oolites are well to very well sorted. Thicker oolite beds consist of several units which may have different grain sizes (Fig. 3). Individual layers of oolite beds correspond to storms or heavy current events. The units can be separated by traces of clayey laminae or thin stromatolitic crusts.

5 Interpretation and Discussion

The widespread Buntsandstein Group consists of red and variegated sandstones and mudstones which are present from Lorraine in France to the Holy Cross Mountains in eastern Poland (Fig. 1). It is a typical terrestrial redbed facies. These red beds are deposited in a large inland basin, the Central European Basin. Braided and meandering rivers brought siliceous grains and mud from the hinterland towards the centre of the basin (Weber 2000). The influx of material fluctuated during time as the climate was regularly changing between arid and less arid or even sub-humid due to orbital movements (Paul and Puff 2010). In certain positions of the orbit, the Triassic mega-monsoon could overlap to central Europe and bring some rain to the drainage area (Parrish 1993). The inflow of water led to large but shallow lakes in the centre of the basin. When the rainy seasons vanished, the water of the lake evaporated, leaving back dissolved ions like calcium, magnesium, sodium, sulfate, and chloride. Microbial calcite producing communities flourished as higher organisms were nearly absent due to rapidly changing environmental conditions. The calcite ooids formed in the shallow environment under the impact of wind and wave action bars or shoals. These several metres thick oolite deposits are present at the margin of the basin and palaeohighs from the Netherlands to Poland (Palermo et al. 2008). Finally, the lakes vanished and small ephemeral rivers reached the centre and brought only mud with them. Frequent desiccation cracks in the mudstones above and below the oolites indicate the shallow water regime. The sediments of the Lower

Buntsandstein are nearly devoid of fossils, body fossils as well as trace fossils. The reason of this scarceness may be not abnormal salinity, but rapidly changing environmental conditions as the shallow playa lake has no buffering capacity against fluctuations of various environmental parameters. The etched surfaces of stromatolites result from the decay of organic matter under a cover of clay or living biofilm led to formation of CO_2, lowering the pH and consequently leading to acidification of the water and dissolution of carbonate.

Some prerequisites of stromatolitic growth can be deduced from observations in the field. Muddy water or mud layers excluded stromatolites or terminated their growth. The microbial community did not survive a mud coverage or muddy water. This effect may be the reason for their restriction to the Eichsfeld Palaeohigh. Here, the sandy and muddy sediments were diverted west and east of the high on their way towards the basin. The more extended areas of oolites indicate that the ooid producing microbes are not so sensitive. The position of stromatolites at top of the oolite beds seems to reflect a directional evolution, most likely of the water chemistry, e.g. alkalinity or supersaturation in respect of calcium carbonate. Perhaps, the stromatolite producing microbial community needs a higher alkalinity than the ooid producing organisms. The lowermost millimeters of mudstones which have direct contact to stromatolites are grayish, not like normally reddish. The decay of the microbial mats after mud coverage led to reducing conditions. The iron(III) of clay flakes was reduced and removed.

The observed photoautotrophy points to cyanobacteria, at least forming a component of the microbial community (Fig. 13). There is a high potential of preservation through the absence of grazers and browsers and an early lithification, although the latter cannot be proved. In several passages of his article, Kalkowsky (1908, p. 112, 115, 119) mentioned and drew sketches of stromatolitic roots. After field observations and his drawings, we believe that thin stromatolitic crusts covering the uneven surface of oolites, served as attachments of larger domes.

Peryt (1975) described stromatolites from the Middle Buntsandstein in the Polish part of the Central European Basin. They are comparable with Kalkowsky's stromatolites, consisting of layered and columnar forms. They are also bound to oolites and oncolites, but grew most likely in a marine or brackish environment, as Peryt deduced from the frequent occurrence of gastropods, foraminifera and spirobid polychaetes.

Regarding the environment of Lower Buntsandstein in northern Germany, there is a long lasting discussion (see Becker 2005, with references herein). Up to now there is no proof that marine incursions or transgressions reached the western part of the Central European Basin during the Lower Buntsandstein.

Stromatolite producing organisms flourished when certain requirements were fulfilled. They needed certain physico-chemical environments, most likely stable substrate, clear not muddy waters, sunlight, high alkalinity, high calcium and carbonate contents of the water, and protection against grazers and burrowers.

The organic nature of stromatolites was generally accepted about 10 or 20 years after the appearance of Kalkowsky's publication. In contrast to that, there was a long-lasting discussion within the scientific community about the formation of ooids. During the nineteenth and twentieth century, most scientists thought of an inorganic origin, such as the precipitation of calcium and carbonate due to supersaturation (Usdowski 1962; Bathurst 1978; Simone 1980; Füchtbauer 1988). Calcite or aragonite may precipitate around a nucleus of a quartz or carbonate grain. Only Kalkowsky (1908) thought of an organic origin produced by colonies of lime secreting phyto-organisms. However, during the last 20 years an increasing number of indications were found that organisms are involved in the formation of ooids (Dahanayake et al. 1985; Davaud and Girardelos 2001; Plee et al. 2006). The in vitro production of ooid-like structures has been observed in cultures of spherical microbial communities (Brehm et al. 2004).

To summarize, Kalkowsky (1908) stated that

p. 100 § 64 Regarding the environment of the oolites in the north German Bunter Sandstone, it is generally assumed that they have formed in a shore facies. One could easily be tempted to think already now of salt lakes as area of their formation.

p. 118 § 88 Stromatolites were always associated with oolites.

p. 123 § 94 Ooids resemble growing bacterial colonies as observed in a Petri dish. Ooids are therefore probably produced by colonies of lime secreting phyto-organisms.

p.124 § 96 We have to assume that simple plants gave rise to limestone precipitation. My aim has been to show that the oolites and stromatolites of the north German Bunter Sandstone are inherently of organic origin.

Taking these statements of Kalkowsky into account, we may say that scientific progress during the last 100 years has not radically changed our understanding of the formation of the stromatolites and oolites of the Buntsandstein, other discoveries have been made that demonstrate that this association has recurred at several Geological Horizons, and is even found forming in modern seas.

Fifty years after Kalkowsky published this classic paper, Richard Chase recognized the first convincing modern analogues of "stromatoliths" around the shores of Hamelin Pool, Western Australia [R. Chase, personal communication to RVB]. Recent investigations of both localities reveal a number of interesting parallels between the environment of Hamelin Pool and that of the Basin with the association described by Kalkowsky. In both cases, stromatolites grow on stable or firm ground in turbulent environments characterized by low sedimentation rates, little fine grained sediment, virtually no terrigenous input, rapid cementation and abnormal or fluctuating salinity.

Kalkowsky's stromatolites occur on the surface of oolite beds. Laminated crusts (called stromatoid by Kalkowsky and interpreted as being formed by syndepositional cementation) also occur in these rocks. Both stromatolites and laminated crusts are concentrated in specific layers traceable throughout quarry faces, where the stromatolites are clearly syndepositional with rippled ooid sand (Fig. 15 in Paul and Peryt 2000). Spongy-fenestrate and fan-like stromatolitic microstructures can be distinguished, and both have undergone intense sparitization. The upper surfaces of some stromatolites are pitted due to syndepositional dissolution. The stromatolites may incorporate variable amounts of ooids, quartz grains and other material.

Hamelin Pool stromatolites also occur in association with ooid sands (Davies 1970; Logan et al. 1974). Subtidal stromatolites grow on rock substrate or crusts formed by penecontemporaneous cementation of marine sands, and are surrounded by mobile oolitic rippled sands and sand waves. The subtidal stromatolites have a laminoid fenestral fabric consisting of ooid and other carbonate sand grains cemented by micritic cements (Logan et al. 1974). Micritisation of sand grains begins soon after deposition and gradually destroys the original structure of the incorporated ooids and other grains (Monty 1976; Reid et al. 2003). Stromatolites in the intertidal zone are thought to be subtidal forms stranded by sea-level fall and modified by intertidal microbial communities (Burne 1991–1992). While the Buntsandstein stromatolites originated in a hyposaline and alkaline lake environment during the high stand of water level, and the Hamelin Pool stromatolites a forming in a hypersaline marine embayment during a period of regression, there are many environmental similarities. In both cases conditions favourable for ooid formation precedes the initiation of stromatolite growth, but the stromatolites co-exist with ooid sands, and incorporate ooid grains into their structures. The morphology of many of the subtidal Shark Bay stromatolites is clearly influenced by the erosive effects of ooid sand waves migrating around them. Once formed, early diagenesis progressively obliterates the structure of ooid grains incorporated into the stromatolites. The association of stromatolites and ooid sands is of considerable geological significance. In another present-day environment the stromatolites of Lee Stocking Island in the Bahamas show a similar association with migrating ooid sand waves to that found in Hamelin Pool (Dill 1991). The association of stromatolites and oolites dates back to the Archean. One of the oldest occurrences of the association is known from the 2.72 Ga Tumbiana Fm., Fortescue Gr. Pilbara Block in Western Australia.

Even the first stromatolites known to science are associated with oolitic limestones, 25 years before Kalkowsky's work was published. James Hall had formally named them *Cryptozoon proliferum*, and they occur in the oolitic Cambrian Hoyt Formation of Saratoga Springs, New York State (Hall 1883).

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