Naturwissenschaften

Stromatolites, Oncolites and Oolites Biogenically Formed in situ

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Observations on ancient and potential (recent) stromatolites reveal that ooids and oncoids, generally described as forming in agitated water, in fact have developed within microbial mats under quiescent conditions. Coated grains grow around various nuclei including biogenic gas bubbles within lens-shaped cavities. Mats in which ooids and oncoids occur as independent or compound bodies had been formed by photosynthetic and/or chemoorganotrophic bacteria or fungi. In their formational environment, the microorganisms building the coated grains will protrude and fuse with the microbial community of the mat. Oolitic beds devoid of organic remains suggest destruction of mats, separation of hard grains, and their subsequent deposition elsewhere. The fresh and outermost microbial coatings of grains may be removed during transportation. The Minette iron ore (Lorraine) is an example of in situ formation of coated grains and stromatolites. The importance of microbial mats in the formation of Europe's largest iron ore deposit is demonstrated.

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"Rolling stones gather no moss"
Titus Livius (Maxim 524)

Ooids and oncoids have fascinated man since time immemorial for both economic and mysterious reasons. They have attracted attention since ancient times under a host of different names. Aristotle and Pliny the Elder called them hammites. Agricola confused hammites and ammonites. The term oolite was coined in 1721 in a review of the topic which also discussed biogenic and abiogenic theories for the origin of coated grains [1]. Scientific queries to find an explanation for the genesis of coated grains such as ooids and oncoids have continued and still continue today [2–6].

Classification of Coated Grains and Bodies

Stromatolites, oncolites, and oolites have been reported from rocks and sediments dating back to the Precambrian. Kalkowsky [2] was the first to carefully analyze stromatolites and oolites. He ascribed a biological origin and an authigenic formation to both structural types, in contrast to many authors, who suggested that ooids form inorganically under high-energy conditions [3]. However, structurally similar but irregularly rounded larger oncoid grains are generally considered to form organically with little or no agitation [4–6]. Various writers have used the terms stromatolite, oncolite, and oolite indiscriminately to describe widely different rocks and sediments. Genetic and descriptive terms have simultaneously been used in such descriptions. As an example, calcretes, geyserites, vadolites, etc., have been described as stromatolites and vice versa, sometimes without any allusion to their origins – be they inorganic or not [7]. Many terms – algal balls, bezoar stone, calculus, hammites, Ketteringstone, oncoid, ooid, pisoid, roestone, vadoid, and a host of others – have been used to describe independent, aggregate- or bed-forming rounded laminated small grains. Suggestions for their modes of formation are numerous. The difficulty in recognizing organic remains in many coated grains such as ooids, pisoids, etc. under the optical microscope led many scientists to advance arguments in favor of an abiogenic origin. On the other hand, the study of recent microbial mat environments where coated grains frequently form shows that chances of preservation of ooids and oncoids are much larger than those

Table 1. Classification of coated grains and bodies

Shape	Tabular, domed or columnar	Regularly rounded	Irregularly rounded
Lamination	Planar to conical	Concentric continuous	Concentric discontinuous
Biogenic individuum	Stromatoid	Ooid[a]	Oncoid
Abiogenic individuum	Stromatoloid[b]	Ooloid	Oncoloid
Biogenic assemblage	Stromatolite	Oolite	Oncolite
Abiogenic assemblage	Stromatoloite	Ooloite	Oncoloite

[a] Grain sizes in both, ooid and oncoid could be indicated by adding prefixes such as micro- and macro-. Often the term pisoid is used for large ooids

[b] Loid = similar (Oehler, 1972; Krumbein, 1983)

of the associated organic material of the matrix [8]. The evolution of carbonate coatings based on organic excretion was observed already in 1535 [9]. However, geologists usually stress the abiogenicity of ooids in particular [10], although several reviews on these grains [6, 11, 12] suggest that they originate mostly under direct or indirect organic participation. Therefore, in view of the current difficulties of nomenclature of coated grains and bodies, we suggest a new classification wherein descriptive and genetic terms are separated. In this classification, we extend an earlier proposal of Krumbein [7] regarding stromatoids, stromatoloids, and stromatolites to rounded laminated structures (Table 1).

Association of Stromatolites, Oncolites, and Oolites through Geologic Time

In this paper, we intend to demonstrate that oolites, oncolites, and stromatolites, as well as their individual units, could form together within the same environment, i.e., within laminated benthic microbial mats growing mostly in tidal flat environments. Occurrences of ooids and oncoids in stromatolitic layers or strata have been reported from the Precambrian to the Recent [13–15]. However, most authors regard ooids and oncoids as being of allochthonous origin. In contrast to their findings, we report some convincing examples of autochthonous growth of coated grains within fossil and Recent microbial mats.

Precambrian Example

In the Precambrian Gunflint iron formation, microoncoids can be seen to occur in pockets within stromatolitic layering (Fig. 1a). These layerings are composed of fine filamentous networks rich in silica and hematite with accessory dolomite. Thin-section studies show that microoncoids often have nuclei representing fossilized microbial mat fragments which could have originated in the neighboring stromatolitic environment, as suggested by the similarity of the filamentous networks. The laminations or mineral coatings of the coated grains are formed predominantly of hematite with interspersed dolomite. These coatings contain organic remains as in stromatolites, but with different orientation patterns of filaments and coccoid-like structures. When the thin sections of samples are studied under oil immersion, the filaments often reveal their branching character. Coated grains are associated with desiccated intraclasts composed of organic relict structures as in the adjacent stromatolites. It is perhaps worthwhile mentioning here that most of the filaments and coccoid-like round spheres of the Gunflint fossilized microbial mats and those of the Hammersley iron formation that we observed in thin sections under oil immersion were strikingly similar to the fungi-derived structures of the Tertiary Warstein iron stromatolites of Germany [16]. Some of the coccoid-like spheres resemble mineral-coated gas or liquid bubbles which may break open and partially deflate to form "*Kakabekia*" structures (Fig. 1b) [16, 17]. Such deflations are frequently observed in laboratory-developed fungal cultures. The ferruginous microoncoids and intraclasts occur in a groundmass of chalcedony and microcrystalline quartz disseminated with carbonaceous material. The coated grains are often assembled in eye-shaped lenses – an arrangement which we refer to as sedimentary "augen structure" – a pattern different from birdseye structures [18]. We observed mineralization to take place preferentially at the formation site of coated grains within recent mats. When comparing these to fossil examples it is evident that the surrounding microbial mat during compaction loses more water and organic matter than the augen structure thus leading to differential compaction and accentuation of the lensoid shape. The inner laminations of Gunflint coated grains are compact and show intense iron mineralization characterized by hematite aggregates. The outer coatings are relatively thick and are irregular in their outlines. They show structures resembling filaments, rods, or cocci embedded in a carbonaceous

Fig. 1. a) Pockets of microoncoids within stromatolitic layers. Note the irregular external coatings of microoncoids which arrange themselves in augen structures. *Arrows* indicate the long axis of the ellipsoidal augen structures (photomicrograph, Gunflint Iron Formation, Ontario, bar 2 mm). b) "*Kakabekia*"-like structures showing the deflation of a mineral-coated gas or liquid bubble? (*center left*) (oil immersion photomicrograph, Hammersley Iron Formation, Australia, bar app. 32 μm)

and siliceous groundmass which is suggestive of an extracellular mucus. The external coatings show irregular outlines that fit vaguely with those of the neighboring grains. This observation suggests that coated grains had initially formed within a composite microbial mat which could later fragment due to processes of degradation and desiccation. As a result, compound coated grains may occur.

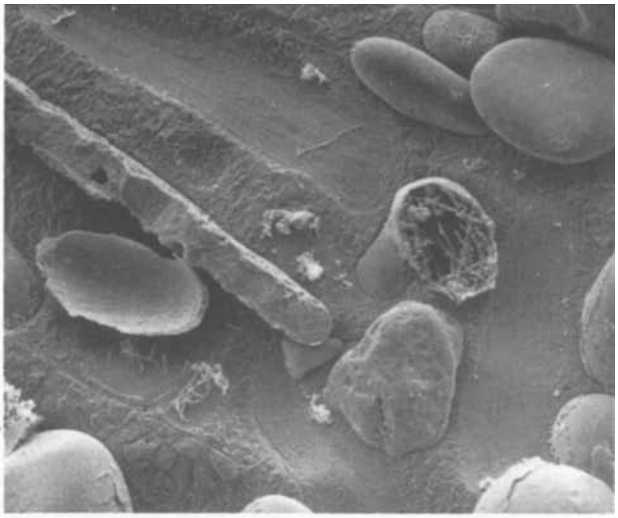
Jurassic Example

Field-oriented vertical sections of the Minette ironstones of Lorraine under controlled etching with dilute HCl reveal that ferruginous ooids and microoncoids occur associated with stromatolitic layers. These show their microbial character by way of well-preserved branching filaments typical of fungal communities and mats (Fig. 2a). Within these layers, characterized by elongated fossil microbial mat fragments, ooids, and microoncoids display the sedimentary augen structure with its long axis parallel to the general stromatolitic stratification (Fig. 2b). Ooids and microoncoids for the most part do not possess a nucleus but instead circular voids (gas or liquid bubbles, as frequently observed in tertiary [16] and recent mats) are observed at the center of these grains under SEM. Some grains rarely could have a bioclast or mineral grain as the nucleus. These, on dissolution during diagenesis, would also generate voids which could be either elongate or irregular in shape.

Within a given lamination of coated grains, the branching filaments were found to be disposed concentrically. The filaments were not transgressive into other laminations in implying the nonboring nature of the organisms that had made the laminations. The groundmass, when etched with dilute HCl, showed envelopes of microorganisms which merged into the outer mineral coatings of ooids and microoncoids. The coatings themselves had been built by envelopes and remainders of mineralized cell parts of the same or different microorganisms (Fig. 2c). Upon etching, organic coatings detached from the dissolving coated grains. The heaviest concentration of iron oxide being around microbial hyphae, we conclude that the Minette iron ore deposit had been produced by microbial activity.

Recent Example

In potential (often called recent) stromatolites of the Solar Lake and Gavish Sabkha, Sinai [19],



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b

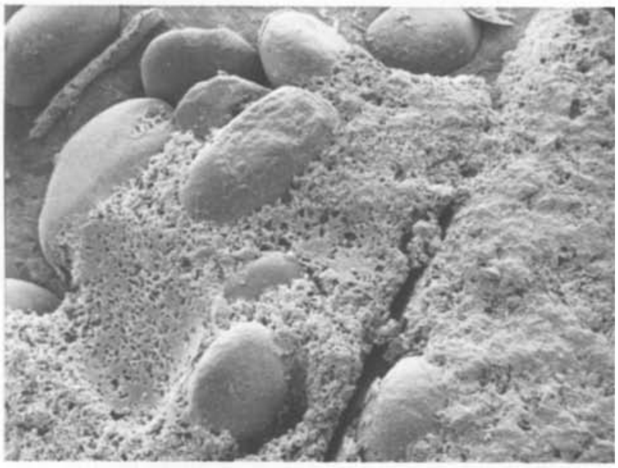

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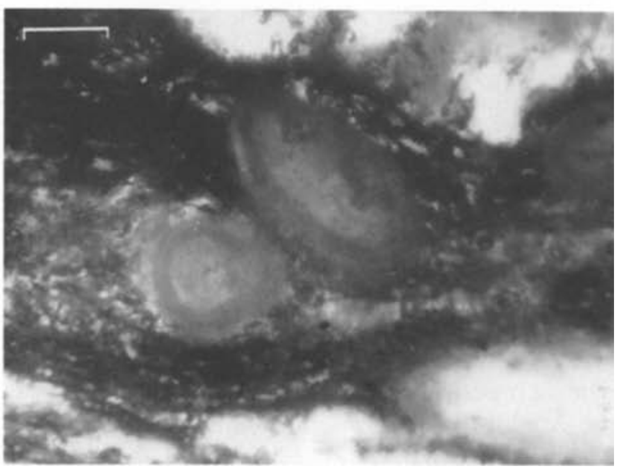
Fig. 2. a) Ooids and microoncoids occurring in association with elongated stromatolitic fragments (*center left*) in a matrix rich in different microbial populations of the mat environment. The microoncoid at the center (*right*) shows the branching microorganisms (most probably fungi) which construct it. b) The arrangement of ooids and microoncoids within an augen structure. *Arrow in center* indicates the axis of the ellipsoidal augen structure. *Other arrows* indicate the stromatolitic fragments which are parallel to the general stratification of the rock. The *upper left* of the augen coating clearly shows remainders of microbial network. c) Ooids and microoncoids within a mineralized microbial mat. Note the partly etched portions of the ooid (*upper left*) which reveal the fungal mat character of its internal coatings. The mat enclosing the coated grains, when further etched, will exhibit a pattern similar to the fungal network of microoncoids (a) (SEM photomicrographs of etched section, Minette ironstone, Lorraine)



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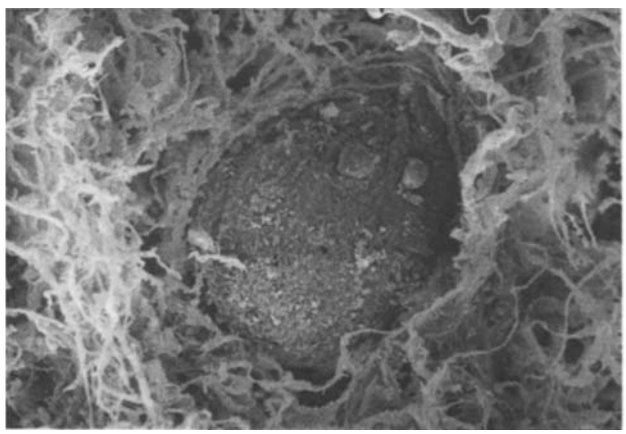

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Fig. 3. a) Ooids and microoncoids (*greyish white*) formed within dark filamentous stromatolitic layers. Note that ooid and microoncoid at the center form part of two splitting ellipsoidal augen structures. The *white areas* are voids in the mat and may eventually develop into coated-grain structures with further bacterial degradation and mineralization (photomicrograph, Gavish Sabhka, Sinai, bar 200 μm). b) Coated grain enveloped within a microbial mat. Note the orientation of the partially mineralized filaments in conformity with the morphology of the grain. While growing, the grain will incorporate more filaments and mineralize. The number of consecutive coatings building up will depend on the environmental and microbial growth conditions (SEM photomicrograph, Solar Lake, Sinai)

ooids and microoncoids are observed within the stromatolitic layers. These also display the sedimentary "augen structure" (Fig. 3a). The filaments of the microbial mat within this structure are more mineralized with hematite than the external horizontal stromatolitic layers. Studies of resin-embedded thin sections and X-ray micrographs show single-coated grains which had transformed themselves to aggregates of ooids or oncoids apparently due to the effects of the overload within the first few centimeters of a mat sequence. Such coalescence of grains produces the layers and pockets which would be identified as ooid or oncoid facies in stromatolitic sequences. In such facies, the sedimentary augen structure is not generally conserved, due to the destructive effects of diagenesis. Toward the bottom of sequences, ooids, and oncoids attain larger sizes and the stromatolitic layers show effects of degradation. Ooids and microoncoids occur within envelopes of microorganisms whose growth pattern follows the morphology of the grains (Fig. 3b). However, a distinct boundary exists between the coated grain and the envelope, and this seems to be due to differential mineralization. Such phenomena suggest in situ growth of ooids and microoncoids within microbial envelopes.

Discussion and Conclusions

The intimate association of ooids and oncoids with the sheath and carbonaceous smooth paste of decaying cyanobacteria of Recent photosynthetic microbial mats, as well as the increasing degree of formation of ooids and oncoids with burial depth, clearly indicate the minimal disturbance which had characterized the growth of these bodies. SEM observations show circular voids at the center of some ooids and microoncoids, suggesting the development of such laminated bodies around a gas (H_2S, CO_2, CH_4 or H_2) or physiological water globules (as is frequent in laboratory-grown fungal iron-precipitating mats) during the degradation of submerged microbial mats [16, 19, 20]. It is worthwhile mentioning here that the "gas-bubble hypothesis" of coated-grain formation was proposed as far back as 1852. Ludwig and Theobald [21] studied in detail the biogenic mineral deposits of a 696-m-long channel of hydrothermal water at the spa of Bad Nauheim (Germany). They found that iron and carbonate precipitation were functions of different microbial communities at different localities. It has also been noted that pisoid growth was initiated by mineral deposition on large gas bubbles within the microbial mats of the channel bed. It has been further stressed that the strong water movement in the channel during the summer tourist season had caused the erosion of the microbial mats, transportation of the pisoids, and their subsequent deposition at deeper points along the channel. Thus, coated grains from a completely degraded and mineralized microbial mat could be washed into another sedimentary environment where they could be subjected to boring or even subsequent growth. Such coated grains deposited in agitated environments could later be cemented with sparite. Sparitic cements could also be due to diagenetic filling of desiccation openings. Therefore, sparitic cements, when present particularly in oolites and oncolites, should be carefully interpreted. In this respect, it is very important to make a distinction between the formational and depositional environments.

We are aware that studies on the morphology of ooids and oncoids and their associated facies lead many to suggest agitated environments and inorganic precipitation processes for the formation of these bodies [22]. This argument is based largely on the scarcity of organic matter in ancient coated grains and their roundness and the association of transported coated grains, particularly ooids, with turbulence-related sedimentary structures such as cross-bedding. It has been shown, however, that "false cross-laminations in carbonaceous silty shales" is produced by microbial mats [23]. We wish to point out here that ooids, pisoids, and oncoids in many cases will not exhibit biogenicity as clearly as in skeletal material. Biogenicity of coated grains is dependent upon oriented expitaxial growth on unorganized protein matrices, growth of small crystals on the cell walls of concentrically growing cyanobacterial or fungal colonies, concentrically oriented crystallization within a chemical gradient created by chemoorganotrophic bacteria which degrade the outermost layer of cyanobacteria or fungi, irregular crystal germination within the slime of cyanobacterial sheaths, growth of repetitive mineral coatings on macromolecules rhythmically or episodically excreted by the organisms into the formational environment, and liquid drops and gas bubbles excreted by the microorganisms into the mat environment. Our observations on laboratory cultures suggest that most of the aforesaid processes would not lead to the eventual preservation of clearly discernible microfossils. In all examples studied – Recent microbial mats and their fossil counterparts from the Jurassic and the Precambrian – the petrological and biological evidence suggests the development of rounded coated grains within microbial mats.

The foregoing description of stromatolites, oncolites, and oolites from widely different stratigraphic levels demonstrates their genesis within the same formational environment. They reflect nothing but transitional stages of the environmental conditions. Our findings underline the role of microorganisms in the genesis of many sedimentary rocks – especially of large ore deposits.

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