The mud-mound system: products and processes

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Abstract
The concept behind the widely used and abused term mud-mound experienced, in four decades, a drifting from its original proposal to describe a puzzling stromatactis-rich calcilutite facies forming the core of some Niagaran reefs (Paleozoic, USA) to one of the three chief carbonate factories on Earth. It encompasses nearly all types of mud-rich buildups. Processes invoked for their accretion are multiple, ranging from trapping and stabilization of loose lime mud by unpreserved soft body organisms or delicate branching organisms, to sea-floor cementation of local accumulation of allochthonous or in situ microbially-produced lime mud, microbially-induced micrite precipitation, and early calcification of microbial and/or sponge tissue.
For nearly three decades, mud-mounds were thought to be essentially a Paleozoic phenomenon. Buildups composed of a mosaic of facies, like for instance the widespread Carboniferous Waulsortians and the Belgian Devonian *récifs rouges* were virtually considered as mud-mound archetypes. However, it is to be noted that the mud-mound facies is only one facies among others in these composite buildups. It is only since the mid-90's that the term mud-mound is widely applied to Mesozoic sponge mounds, a mound type of particular interest to understand the mud-mound phenomenon. Except for those sponges with welded siliceous spicular skeletons, sponge soft tissue diagenesis is needed to preserve sponge body fossils, and consequently to obtain sponge mounds. It has been shown that there is a continuum of preservation between sponge mounds with well-preserved sponge body fossils on the one hand, and stromatactis-rich spicular mounds on the other hand.
We advocate that, while the reef system relies essentially on biomineralization processes to operate, the mud-mound system relies mainly on organomineralization processes to successfully accrete mounds through calcite nucleation on dead organic matter. The organomineralization produces an automicrite network into which one or several generations of mud successively infiltrate, producing a distinctive polymud fabric. When present, the remaining open cavity system is either cemented in the marine to shallow burial environment by isopachous Ca-carbonate crusts giving rise to stromatactis, or filled with another mud generation producing inhibited or aborted stromatactis. Mud-mounds are consequently diagenetic buildups that would not exist without the action of organomineralization.

Text for slide show
(Numbers refer to slide number)

(1) Among the various carbonate bodies in the geological record, those mound-shaped buildups that geologists are used to call mudmounds, were perceived for decades, and are still perceived by most workers as enigmatic.

(2) Since its original proposal, the mudmound concept has differed widely from one worker to the next, and nowadays, it unfortunately encompasses nearly all types of mud-rich buildups. The aim of this talk is to propose that not any mud-rich buildup should be called mudmound.

(3) The term mudmound was originally coined by Textoris in the mid-sixties to designate the stromatactis-bearing calcilutite basal facies of Silurian reefs that was lacking frame building organisms.

(4) However, the term rapidly evolved to designate much larger structures.
Everyone knows this famous shelf profile, and its foreslope mudmounds.
This figure had a profound influence on subsequent work dealing with mudmounds. It is clear, from the examples Wilson cited, that the term mudmound rapidly had evolved to encompass buildups much larger than intended by Textoris and composed of more than one facies

(5) At the beginning of the nineties, Noel James and I attempted to make a clear distinction between two types of carbonate buildups: reefs and mounds, both distinguished on their ability, or inability, to build structures that potentially resist significant wave or current energy.
(6) We distinguished two broad types of mounds: those controlled by living organisms, the biogenic mounds, including skeletal and microbial mounds, and the mudmounds, whose accretion was not controlled by living organisms. Unfortunately, we failed to discuss the processes involved in mudmound accretion.

(7) During the three last decades, several processes were invoked for the accretion of mud mounds.

(8) For a while, and based on comparison with the modern, mudmounds were viewed as structures built by sediment trapping by non-calcareous organisms, or by delicate branching organisms like the fenestrate bryozoans.

(9) In the mid-seventies, Claude Monty started to develop his idea that … (10) mudmounds represent a mega-development of microbial textures. This idea was so widely accepted that it became rapidly a paradigm, not to say a dogma. The paradigm was later formulated by Monty in this well-known IAS mudmound book: “mudmounds are microbial buildups controlled by bacteria and cyanobacteria as primary producers”.
The microbial paradigm to explain mudmound origin dominated all other propositions during at least two decades. And although the microbial approach definitely constituted a significant step in our understanding of the mudmound question, in my opinion such domination inhibited self-questioning, as well as innovative approach and creative science.

(11) Robin Bathurst was among the first to draw attention to the necessary role of early sea-floor lithification in mudmound accretion.

(12) Slightly after, I proposed with Hélène Gignac, a mechanism different from the one proposed by Bathurst for the mudmound induration: early lithification occurred in the first meters below the sediment/water interface, rather than at the sea-floor, through calcification of a sponge tissue during decay of the organic matter.

(13) In the mid-nineties, the Joachim Reitner and Fritz Neuweiler team developed a new process-based approach to mudmound research, in applying organo-chemical methods to explain calcification processes. The approach was combining both, the concept of organomineralization, and the concept of matrix-mediated biomineralization.
Importantly, this innovative approach in the study of mudmounds pointed to the existence of a new category of sedimentological facies: those derived from calcite precipitation related to organic macromolecules.

(14) In terms of modes of carbonate buildup production in the marine benthic realm, we consider that three basic groups of interacting processes are generally in force: *biomineralization*, *organomineralization*, and *cementation*.
(15) Biomineralization is a process that pertains to bios, to living matter. It is the precipitation of a mineral deposit in close association with the cell. The movement of ions, from the surrounding medium to the cell, is under the control of life forces.
Organomineralization is a process of mineral formation in close association with non-living organic substrates in sediments. It differs from biomineralization by the lack of intracellular control and by the influence of diagenesis.
Cementation consists of space-filling crystals that grew attached to a free surface.

(16) Although the three modes of carbonate production may act concurrently in the making up of a buildup, we advocate that two main carbonate systems are responsible for the accretion of carbonate buildups. At the one end, reefs and biogenic mounds are buildups predominently constructed by the interaction of biomineralization and cementation processes. At the other end, mudmounds are buildups accreted predominantly by the interaction of organomineralization and cementation processes.

(17) There are two important aspects concerning the products of the mudmound system.

(18) First, mudmounds are not only dominated by fine-grained carbonates, but they possess a distinctive fabric: the polymud fabric, a fabric described by Alan Lees and John Miller from the Waulsortian mounds. This fabric is a direct product of the interaction of organomineralization and cementation. It consists of a highly structured mixture of mud generations that always show successive geopetal relationships.
(19) Although it can be observed macroscopically on polished slabs, like here where we can see a number of mud generation, **(20)** the fabric is better observed in thin-section. For instance, this is a typical stromatactis limestone from the Frasnian mounds of Belgium. The first “mud” generation is represented by a microspar rich in sponge spicules locally still forming a meshwork. Based on geochemical work on that type of facies in the Paleozoic and the Mesozoic, we interpret that this initial rigid network is the result of organomineralization of dead sponge organic matter, and that a cavity system developed in it by more or less concurrent collapse of uncalcified parts. Subsequently, alternating cementation and geopetal mud infilling occurred in this initial rigid spiculate microspar network, giving rise finally to the polymud fabric we observe.

(21) The second aspects concerning the products of the mudmound system is that only part of what is commonly viewed as typical mudmounds is the product of the mudmound system. Let me show you two classical examples Wilson cited as good representatives of his foreslope mudmounds.

(22) The first example is the Frasnian so-called “récifs rouges” of the Belgian Ardennes. Claude Monty viewed them as typical mudmounds. In a simplified manner, they are composed of four main superposed facies forming a shallowing upward sequence. The basal facies is the classical stromatactis-rich red lime mudstone to wackestone, nearly devoid of fossils, except for ubiquitous sponge spicules, and a few poorly preserved sponge body fossils.
The overlying facies is the same as the basal facies, but with the addition of platy corals, not abundant enough though to make up a frame.
Above is a more diversified coral, stromatoporoid and skeletal algae wackestone to packstone, still with stromatactis. In places, skeletal organisms strat to make up a framework. All three facies exhibit a polymud fabric and have ubiquitous sponge spicules.
The uppermost facies consists of a stromatoporoid, coral and bryozoan framework strengthened by various microbial and calcimicrobial encrusters.

(23) Plotted on our ternary diagram according to the inferred processes that have controlled its accretion, the basal stromatactis limestone would be a pure product of organomineralization and cementation, as well as facies F2, even if sparse skeletal platy organisms start to occur. Part of the third facies has been built by skeletal organism, indicating that biomineralization became increasingly significant. This facies constitutes a transition between unequivocal mudmound facies, and finally the upper skeletal-microbial limestone where biomineralization processes obviously dominated. An entire buildup then represents an evolution from mudmound to biogenic mound facies, transgressing both systems. It is a composite buildup that cannot be globally called mudmound.

(24) In a similar manner, the four basic facies of the Waulsortian-type buildups transgress the two systems. Two facies are particularly interesting here. The largest volume of the buildup is made up of a sponge-fenestrate bryozoan mudstone and wackestone. **(25)** In thin-section, typical polymud fabric is observed, and as in the Frasnian mounds, the initial rigid network was formed by spiculate microspar. The fenestrates are commonly broken and do not form a framework. Possibly, they were attached to a sponge ephemeral substrate. **(26)** The accretion of this facies would also have been controlled mainly by organomineralization and cementation processes. Locally, the fenestrate bryozoans built a delicate framework, in the absence of sponges and devoid of mud, forming a cementstone containing up to 90% of early fibrous cement. Obviously this facies is related to biomineralization and cementation.
As for the Frasnian buildups, the Waulsortian-type buildups cannot be called mudmounds as they are commonly called.

(27) Finally, the Niagaran buildups present the same situation as the two other examples. Our conception of mudmound brings us back to the original object of Textoris.

(28) To conclude, we propose that:

- not all mud-rich, mound-shaped nuildups are mudmounds,

- mudmound is a carbonate buildup whose accretion was not controlled by organisms
- mudmound is the product of a distinct carbonate system based primarily on organomineralization and cementation processes;
- it is a diagenetic buildup, or part of a larger composite buildup, that would not exist without the action of organomineralization.