Petrographic and mineralogical characterization of Middle Jurassic thrombolites (High Atlas, Morocco)

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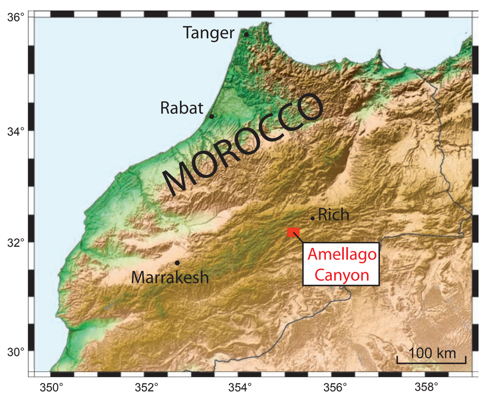
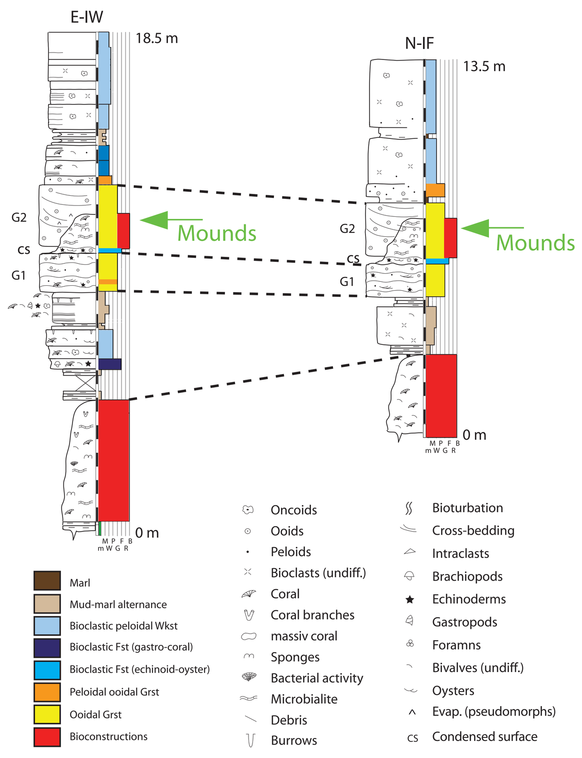
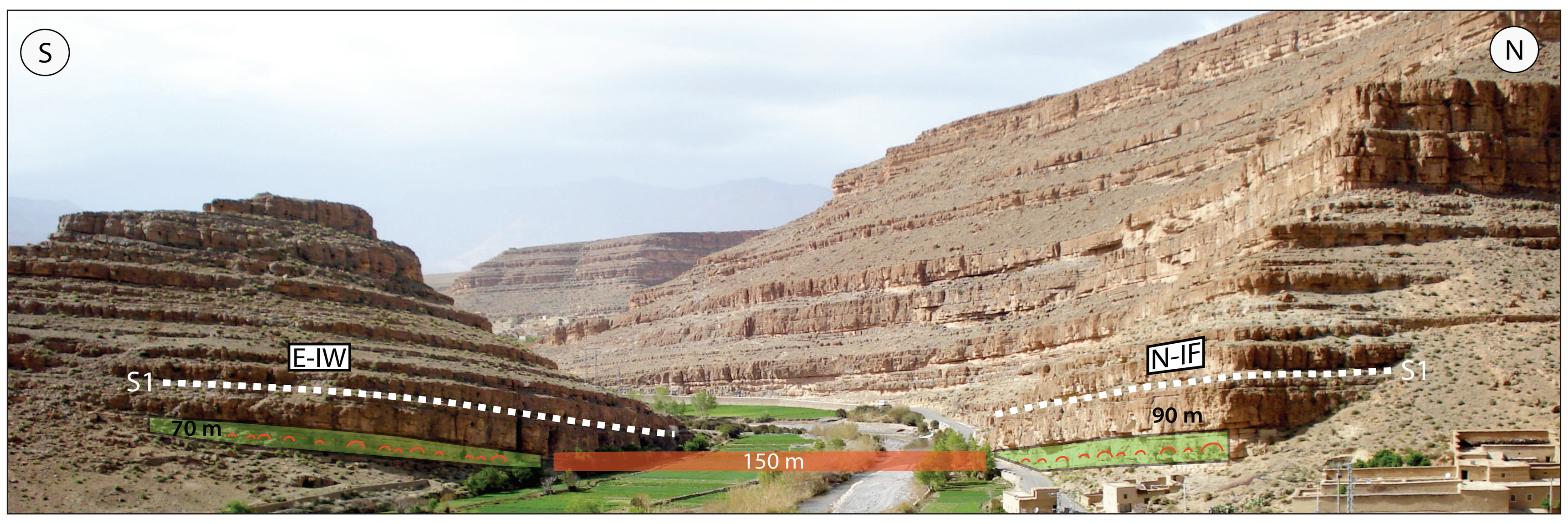
1. Geologic and stratigraphical setting



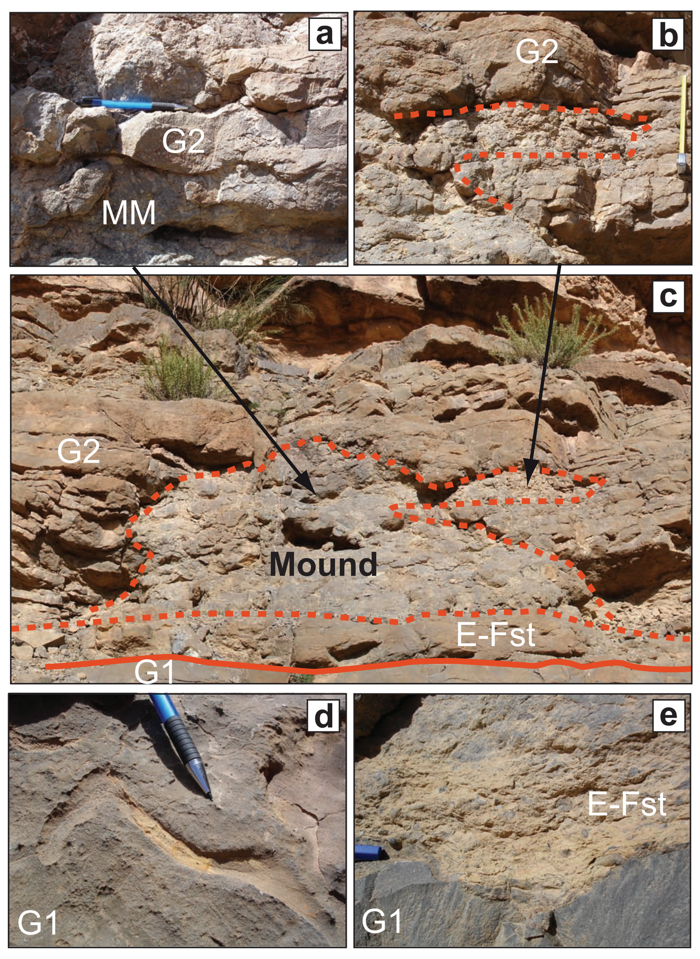
The studied Middle Jurassic microbial mounds crop out in the Amellago Canyon, located in the central part of the High Atlas Mountain range of Morocco. During the Bajocian shallow-water carbonate-terrigenous mixed sediments accumulated along a gently steeping ramp. The studied succession, up to 100 m thick, belongs to the Assoul Fm and mainly consists of lagoonal facies, ooid shoals and bioconstructions.



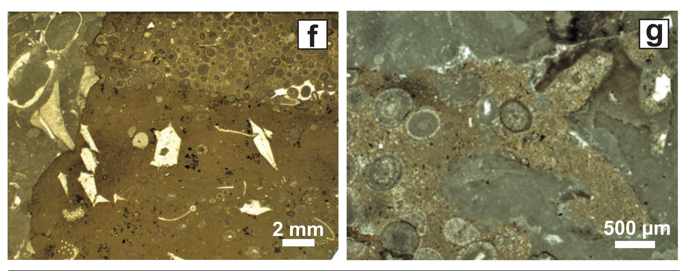
For the study of the microbial mounds two locations have been selected: one, East Island Wall(E-IW), is ~70 m long and the other one, North Island Face (N-IF), has a length of 90 m. The studied deposits belong to the same stratigraphic interval and can be correlated with each other in both localities. The stratigraphic succession startswith a coral-microbial reef, which is followed by bioclastic wackestones/floatstones and marly deposits. Overlying the marls a package of ooidal-peloidal grainstones were deposited. Enclosed within this interval the microbial mounds occur.

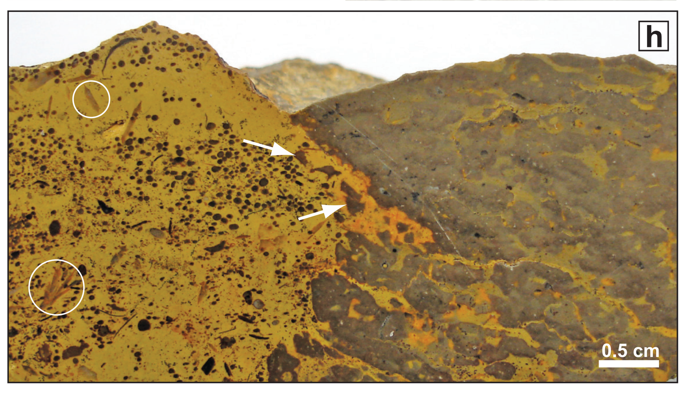


2. Microbialite structure



The microbial mounds (c) appear embedded in a 4-m-thick package composed of peloidal-ooidal packstones and grainstones. This package can be subdivided into two parts, one part below the mounds (G1) and the other one lateral and above them (G2). G1 has a wavy and planar cross-bedding and the topmost surface shows abundant horizontal burrows (d). This surface represents an interval of condensation and shows a sharp contact (e) with an overlying layer of echinoid-oyster floatstone (30 cm thick) . This layer may have acted as a stable,hard substrate for the settlement of the mounds.
G2 is characterized by high angle (22°) trough cross-bedded ooidal grainstones. The mounds are enclosed within these grainstones and interfinger laterally. In the contact region with the mound, crystals of calcite pseudomorphs after gypsum occur in the ooidal shoals. The crystals show concave boundaries with the surrounding sediment (f). These concave boundaries indicate that the sediment was not fully lithified at the time when the gypsum precipitated.



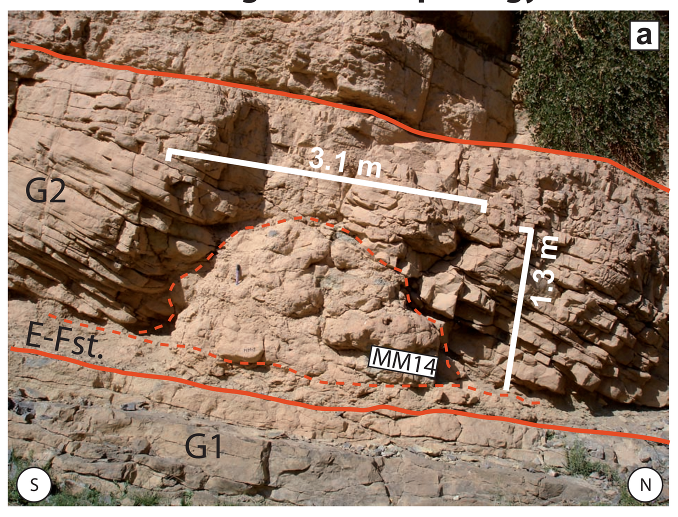


In the field complex interfingering relationships between the mounds and shoals have been documented (a, b). However the studied polished slabs (h) and thin-sections (f, g) clearly show a sharp and erosional contact between both carbonate bodies. Sometimes fragments of the microbialites are incorporated in the ooid shoal (white arrows in Fig. h). Ooids are not trapped or bound within the microbialite fabric, although occasionally they have been recognized in some of the cavities of the microbialite.These observations point out that both carbonate bodies were not growing simultaneously. First, the mounds established upon a condensed surface and after during the deposition of the shoals, they became truncated and covered by the shoals.

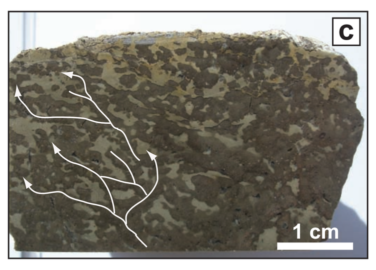
3. Petrography and composition

3.1 Macrostructure

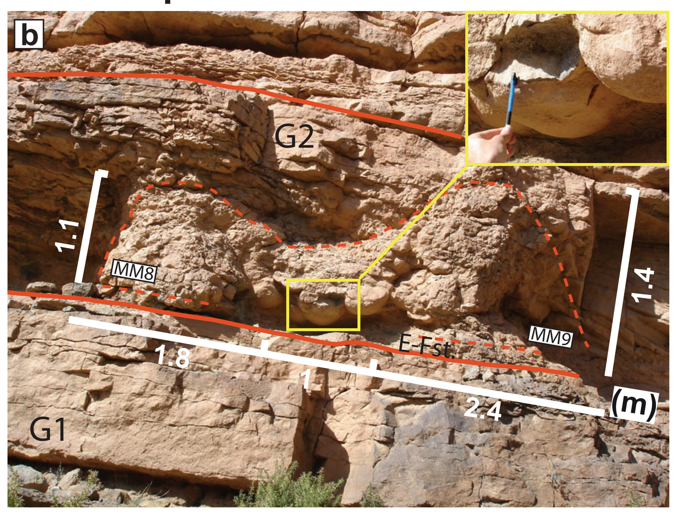
Domal growth morphology



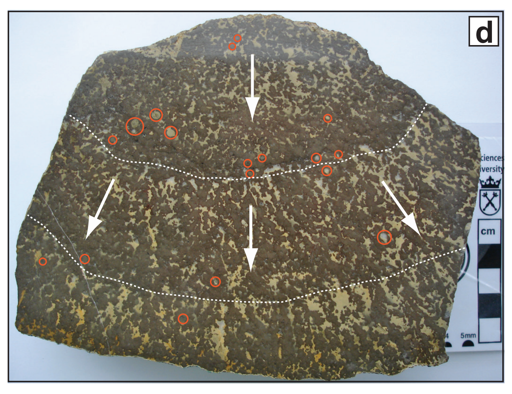
	E-IW	N-IF
height	0.5 - 2.2 (ø1.2)	0.7-3.2 (ø1.4)
width	1.2 - 3.3 (ø2.5)	1.3 - 4.7 (ø2.45)



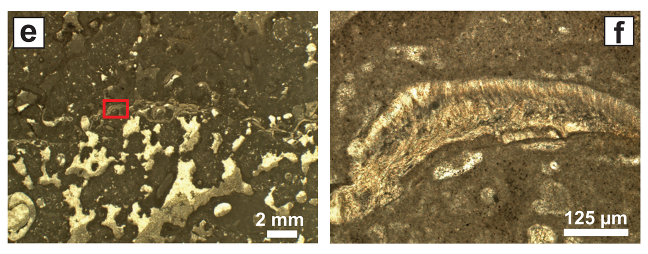
Hemispheroids between two domes



The studied mounds exhibit high-relief domal growth morphologies (a) of approx. 1.3 m height and 2.5 m width (n=28). This represents a preferential lateral growth direction. The mean space between individual mounds is ~ 2.7 mThe microbialites have a macroscopic clotted fabric and no internal lamination, consequently they are classified as thrombolites (Aitken, 1967). The detailed analysis of 25 polished slabs revealed that the thrombolites mainly develop branching growth forms (c, d). These branches are 0. 5 - 2 mm thick and radially arranged, showing mainly horizontal growth. In the interspace between the branches, irregular shaped growth framework cavities were formed. Occasionally, the mounds are connected laterally, bridgelike with pendant nodular hemispheroids growing downward in the interspace (b). The hemispheroids are approx. 25 cm thick and 50 cm in diameter.

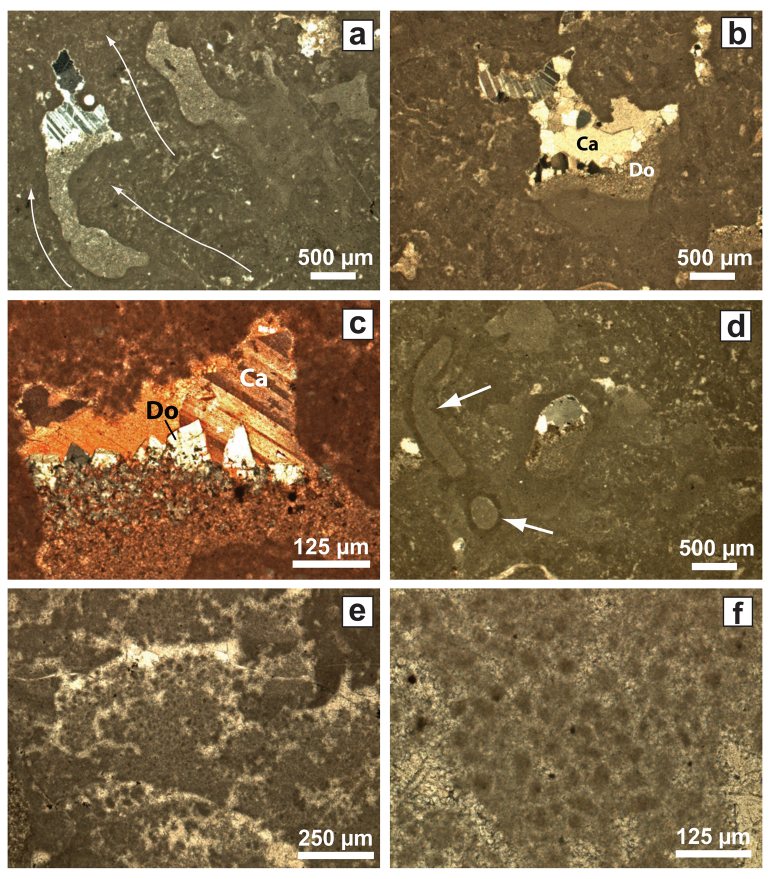


Different growth stages can be identified, expressed by the occurence of a continous band with abundant encrusters such as bivalves and bryozoans (e, f). During these intervals bivalves frequently bore the outer surface of the microbialites (red circles in Fig. d). The occurence and development of the downward growing hemispheroids is related to low to zero sedimentation rates (Leinfelder et al.,1993). Furthermore, this peculiar growth forms have been frequently documented in Jurassic thrombolites (Leinfelder and Schmid, 2000).



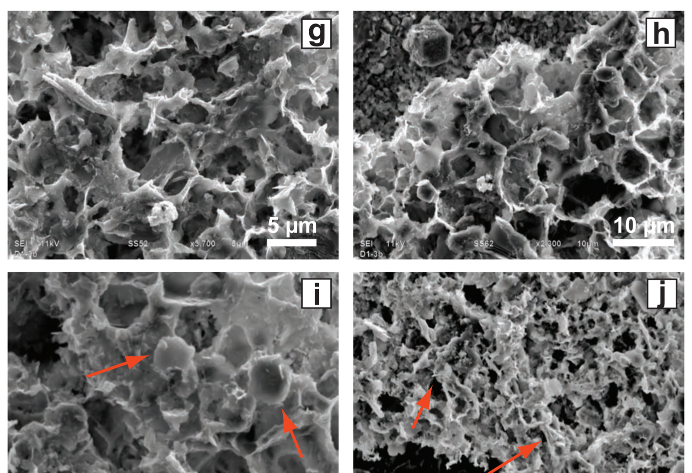
3.2 Mesostructure

The thrombolites are composed of dark mesoclots (40 - 70%), which are characteristic for their distinct, clotted fabric (a, e). These polymorphic clots occur in clusters and interconnect with each other to form aggregated assemblages of micrite. In the interspace between the mesoclots irregular shaped growth framework cavities were developed. They make up to 10 - 30% of the thrombolite total volume and are usually flat and elongated with a height of 3 mm and a length of 5 mm. The cavities can be partially or totally filled with fine-grained sediment and calcite. Geopetal fillings have been observed (a,b). Also dolomitization occurs inside some cavities (c). No allochthonous particles or cryptic biota are present inside the cavities.
Skeletal components also occur inside the thrombolite fabric, e.g. bryozoans, small branching corals and sponges. The thrombolites often have horizontal and vertical borings (f), which are indicators of their early lithification.



3.3 Microstructure

The mesoclots are composed of 60 - 200 µm wide dark, micritic peloids (f), which are surrounded by sparry calcite (e). The peloids occur isolated or as densly packed clusters.

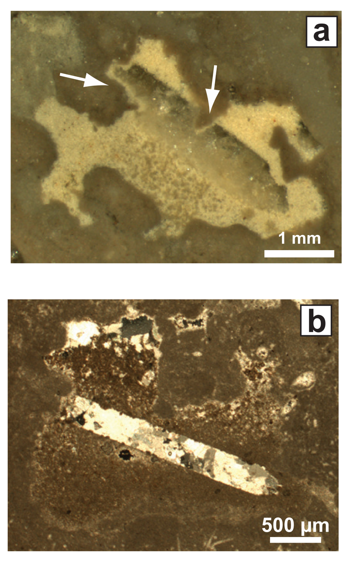


SEM examinations of polished and slightly etched thrombolite rock chips, reveal the presence of subpolygonal, honeycomb-like patterns (g, h). Individual subpolygonal to rounded pits (5 – 10 µm in diameter) are separated by distinct walls with a flaky shape. Inside the pits or distributet in the meshwork spherical, egg-like masses (1 – 3 µm) occur (i). The shape and size of these spheres fits well to those of known modern bacteria and therefore they are interpreted as fossilized bacterial coccoids. Also twisted filamentous, rod-like bacteria forms (5 - 25 µm long) appear coalesced inside of the subpolygonal pattern (j).

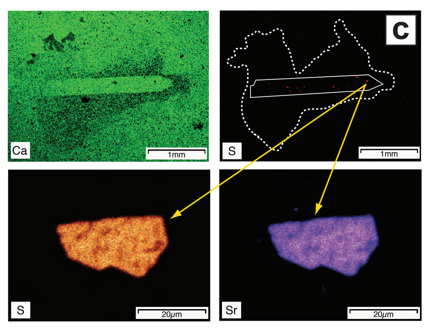
Kazmierczak et al. (1996) interpreted similar structures with abundant spheroids and filaments from the Jurassic as remnants of calcified coccoid cyanobacterial mats.

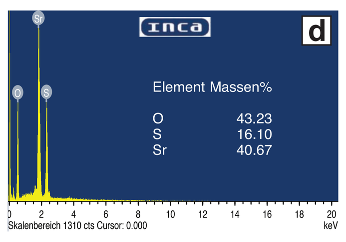
4. Mineral structure

Mineral structures composed of calcite pseudomorphs after gypsum and hematite pseudomorphs after framboidal pyrite were found inside the thrombolites. The occurrence of these minerals is mainly restricted to the growth framework cavities.

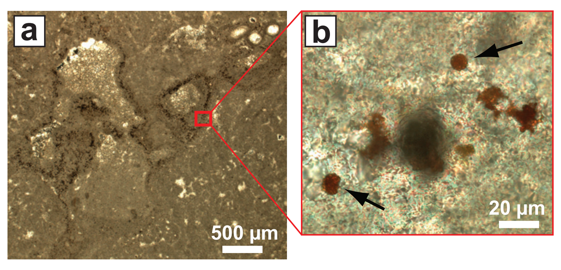


The calcite pseudomorphs after gypsum are lenticular (~4mm long) and have been found exclusively inside the growth framework cavities of the thrombolite (a, b) and in the shoal deposits in close contact with the mounds. It is obvious, that these crystals precipitated inside the cavities, since the crystals often adapt to the shape of the cavities (a). The gypsum (CaSO4 2 H2O) has been almost completely replaced by calcite; just some minor sulfur inclusions are present in the crystals (c).

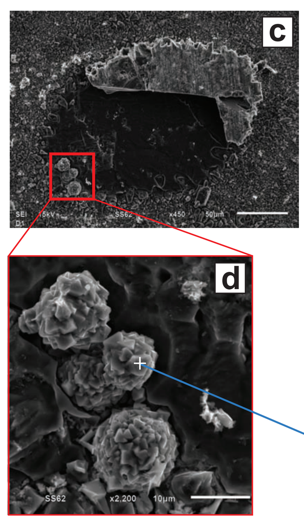




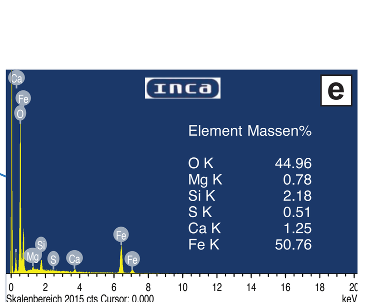
The small sulfur-rich inclusions consist of celestite (SrSO4), which commonly occur associated with gypsum (d).

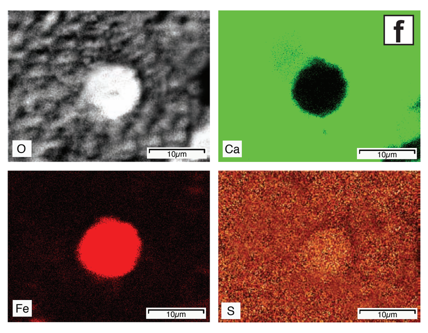


Small grains of iron oxides appear dispersed throughout the whole thrombolite, often forming bands that rim the growth framework cavities (a). These dark red bands are made by rounded mineral aggregates (b).



When observed with the SEM the rounded aggregates show a framboidal texture, which is exlusively formed by pyrite (Farrand, 1970). These spheroids are 5 - 15 µm in diameter (d) and occur in clusters of 4 or more specimens, often near cavities (c). The elemental composition, obtained with the EDX, reveal that the framboids were later oxidized into hematite (e). Despite the small amounts of S (< 1%) measured in the framboid (f).





5. Discussion and conclusion

1. Alternation with shoals
The mounds occur on top and embedded with ooidal shoals. The mounds developed directly upon a condensed surface with horizontal burrows, which occur at the top of the underlying shoal. A sharp contact between this surface and the mounds is observed. Moreover mounds are eroded by the shoals, indicating they were not coeval.

2. Morphology
The mounds developed in subtidal shallow water environments. The domal forms of ~ 1.3 m height with preferential lateral growth indicate certain limitation in the available accommodation space. The pioneer settlement of these mounds is represented by a basal layer with a high accumulation of echinoids and oysters.

3. Internal structure
The resulting clotted peloidal fabric of the thrombolithes was formed *in situ* by bacterial calcification, whereas trapping and binding of allochtonous grains were insignificant.

4. Mineral structure
The presence of former gypsum crystals is probably related to arid periods. In such periods higher restricted conditions with evaporation rates exceeding precipitation rates would have occurred. Framboidal pyrite is linked to S-reducing bacterial that decay organic matter in an anaerobic environment or microenvironment.

5. Biogenic structure
Subpoligonal patterns are identified within the thrombolites. Filamentous (5-15 µm long) and coccoidal bacterial forms (1 – 3 µm diameter) are observed within these subpoligons. They probably represent fossilized bacterial remains.

6. Summary
All these data indicate that mounds are not coeval with the ooid shoals. Their alternance is probably related to the interplay of climatic changes (arid vs. non-arid periods) and sea-level fluctuations.

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