

Microbially induced cementation of carbonate sands: are micritic meniscus cements good indicators of vadose diagenesis?

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ABSTRACT

Characteristic fabrics such as micrite envelopes, calcified filaments and micritic grain-to-grain bridges are observed in a modern subtidal firmground (Wood Cay, Bahamas) and in a variety of firm- and hardgrounds of Lower Cretaceous and Upper Jurassic platform carbonates (Swiss and French Jura Mountains). Their similarity to microbial fabrics described in grapestones and in intertidal to continental vadose environments suggests that microbial activity played an important role in the initial stabilization and cementation of carbonate sands. 'Meniscus-type cements' (to distinguish them from vadose meniscus cements), which clearly formed in subtidal environments, are related to filament calcification, trapping of percolating micrite and microbially induced carbonate formation. Such meniscus-type cements are commonly micritic, but meniscus-shaped precipitation of fibrous aragonite or sparitic calcite around organic filaments is also observed. Therefore, an interpretation of vadose early diagenesis should not be based on meniscus cements alone. Similarly, subtidally formed filamentous structures can strongly resemble alveolar septal structures and be interpreted incorrectly as related to subaerial exposure.

Keywords Carbonates, cements, diagenesis, microbial activity.

INTRODUCTION

Differential early cementation of the sea floor and the formation of firm- to hardgrounds have been widely recognized in the rock record and in modern sedimentary environments (e.g. Purser, 1969; Shinn, 1969; Dravis, 1979; Fürsich, 1979; Garrison *et al.*, 1987). Physical factors favourable to such early cementation include low rates of sedimentation, sediment stability and high initial sediment permeability (Shinn, 1969; Bathurst, 1975). Increased pumping of sea water through the sediment is thought to drive the precipitation of acicular aragonite and cryptocrystalline high-Mg calcite in environments at least intermittently exposed to high-energy conditions (Tucker & Wright, 1990; Molenaar & Ziljstra, 1997). In only

a few cases, however, has the activity of endolithic and chasmolithic (occupying empty pore space) organisms, such as bacteria, fungi, diatoms and foraminifera, been identified to contribute to hardground formation (e.g. Dravis, 1979). The current study suggests that stabilization and initial cementation in shallow marine carbonate sands can largely result from microbial binding and microbially induced precipitation of calcite and aragonite. The following sections provide a short review of classical interpretations of the sedimentary fabrics observed in this study (meniscus cements, micritic envelopes, calcified filaments) and point out why care must be taken when using such fabrics to constrain early diagenetic environments.

Meniscus cements

Meniscus cements are defined as cements with rounded surfaces and a pore-rounding habit

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located predominantly near grain contacts (Dunham, 1971). They are described as being indicative of vadose environments, where they have grown to conform to the air–water interface of droplets held by capillarity in pores partly filled by air (Dunham, 1971; Longman, 1980). Initially restricted to sparitic calcite precipitates, other authors have extended this interpretation to micro- or cryptocrystalline meniscus cements, which consist of aragonite or high-magnesium calcite, commonly observed in beachrocks (Meyers, 1987; El Moursi & Montaggioni, 1994; Neumeier, 1998). Bernier & Dalongeville (1988) mentioned micritic meniscus cements in association with micrite envelopes in intertidal environments and suggested that they formed by cyanobacterial grain stabilization and trapping of micrite in the filament mesh.

Micrite envelopes and filamentous fabrics

Carbonate grains with micrite envelopes were defined as cortoids (coated grains) by Flügel (1982). Two main types of envelope formation can be distinguished. Destructive micrite envelopes are formed by the infill of vacated borings of endolithic microorganisms such as cyanobacteria, fungi and bacteria (e.g. Bathurst, 1966; Friedmann *et al.*, 1971; Kobluk & Risk, 1977a). Accretionary or constructive micrite envelopes are the result of calcification of filaments of epilithic organisms protruding into empty pore space (Kobluk & Risk, 1977a, b; Calvet, 1982; Wright, 1986). Trapping and/or precipitation of micrite in a carpet of filaments or in sheaths of organic mucus may contribute to envelope formation and the binding of grains (e.g. Kobluk & Risk, 1977b; Dravis, 1979; Feldmann, 1997; Webb *et al.*, 1999).

Micrite envelopes containing organic filaments or their calcified remains are very common in modern and fossil marine carbonate environments. They have been described in intertidal environments and beachrocks (e.g. Bricker, 1971; Meyers, 1987; Bernier & Dalongeville, 1988; Strasser *et al.*, 1989; El Moursi & Montaggioni, 1994; Neumeier, 1998). Purser (1969) observed a close association of ‘pore-lining microcrystalline cements’ with clearly subtidal hardgrounds in the Paris Basin, and Friedmann *et al.* (1971) described occurrences of microbial micrite envelopes in water depths of around 75 m in the Pleistocene of the Atlantic shelf.

Formation of micrite envelopes also occurs in supratidal to continental vadose environments (James, 1972; Calvet, 1982; Wright, 1986, 1994).

Typical filamentous microorganisms in vadose continental environments include fungi, bacteria, lichen, cyanobacteria and root hairs of vascular land plants, which colonize pore space and grain surfaces and bore into grains and cement (Kahle, 1977; Klappa, 1979; Calvet, 1982; Southgate, 1986; Wright, 1986; Phillips *et al.*, 1987). They are commonly calcified by microcrystalline low-magnesium calcite with a wide range of crystal habits. Fungal filaments that surround rootlets can form calcified irregular networks or ‘arcuate septa’ within pores (Klappa, 1979, 1980; Wright, 1994). They are termed ‘alveolar septal structure’ and are characteristic of calcretes and palaeosol formation (Wright, 1994).

Processes of biogenically induced calcification

Initially, it was thought that biogenically induced calcification was caused mainly by an increase in pH resulting from CO₂ degassing by autotrophic organisms during photosynthesis and, thus, facilitated carbonate precipitation in their surrounding microenvironment (e.g. Bathurst, 1966; Pentecost & Riding, 1986). However, considering the abundance of calcified filaments and micrite aggregates in cryptic environments (in the absence of light), heterotrophic metabolisms capable of initiating carbonate precipitation are common (e.g. Friedmann *et al.*, 1971; Bauld, 1981; Kennard & James, 1986; Chafetz & Buczynski, 1992; Leinfelder *et al.*, 1996; Feldmann, 1997). Various metabolic pathways induce carbonate precipitation by modification of the environment around the microbes (e.g. increase in pH by CO₂ removal, increase in carbonate alkalinity through CO₂ degassing and ammonia production). Detailed information on the chemistry of the possible metabolic reactions can be found in Castanier (1987), Castanier *et al.* (1997) and Ehrlich (1996).

The important point is that the presence and abundance of organic matter in the sediment is the main factor controlling the development of heterotrophic bacteria and the content of Ca²⁺-binding, acidic macromolecules. Both heterotrophic bacteria and acidic macromolecules are responsible for an important part of organically influenced carbonate formation (e.g. Reitner, 1993; Ehrlich, 1996; Castanier *et al.*, 1997).

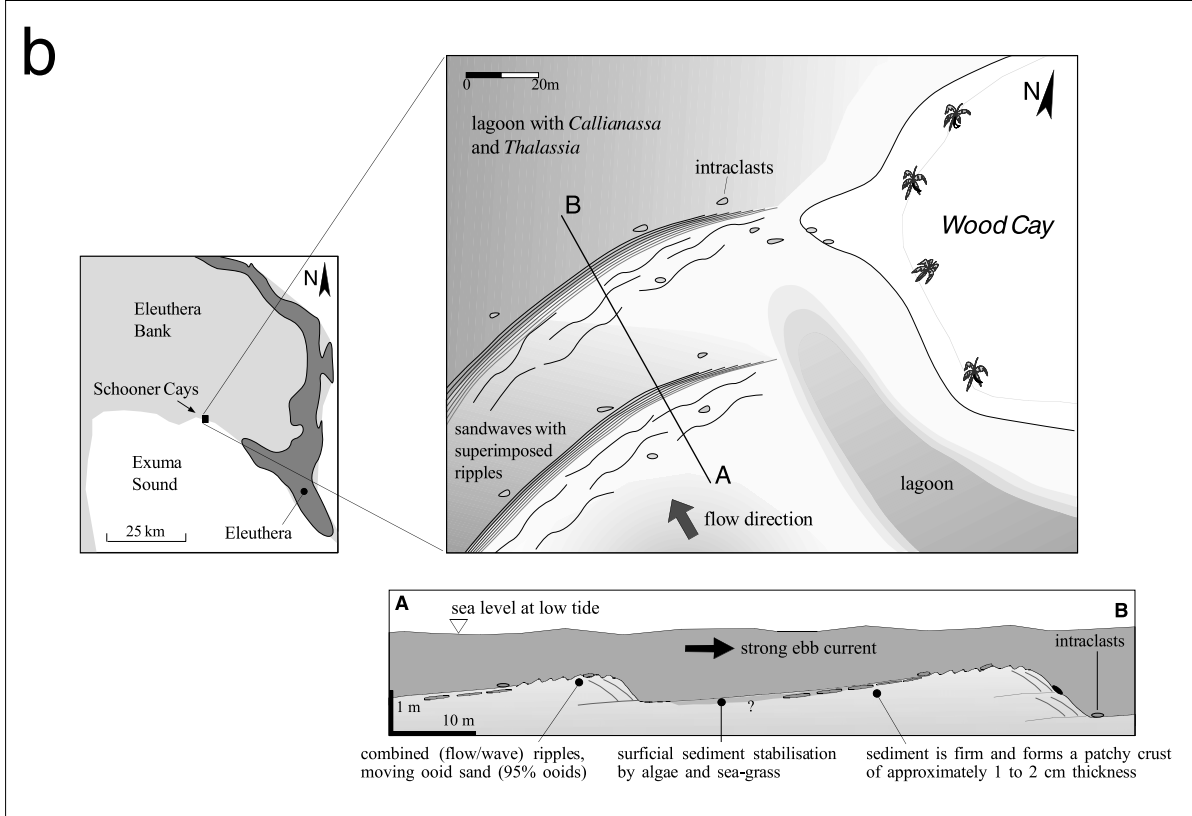
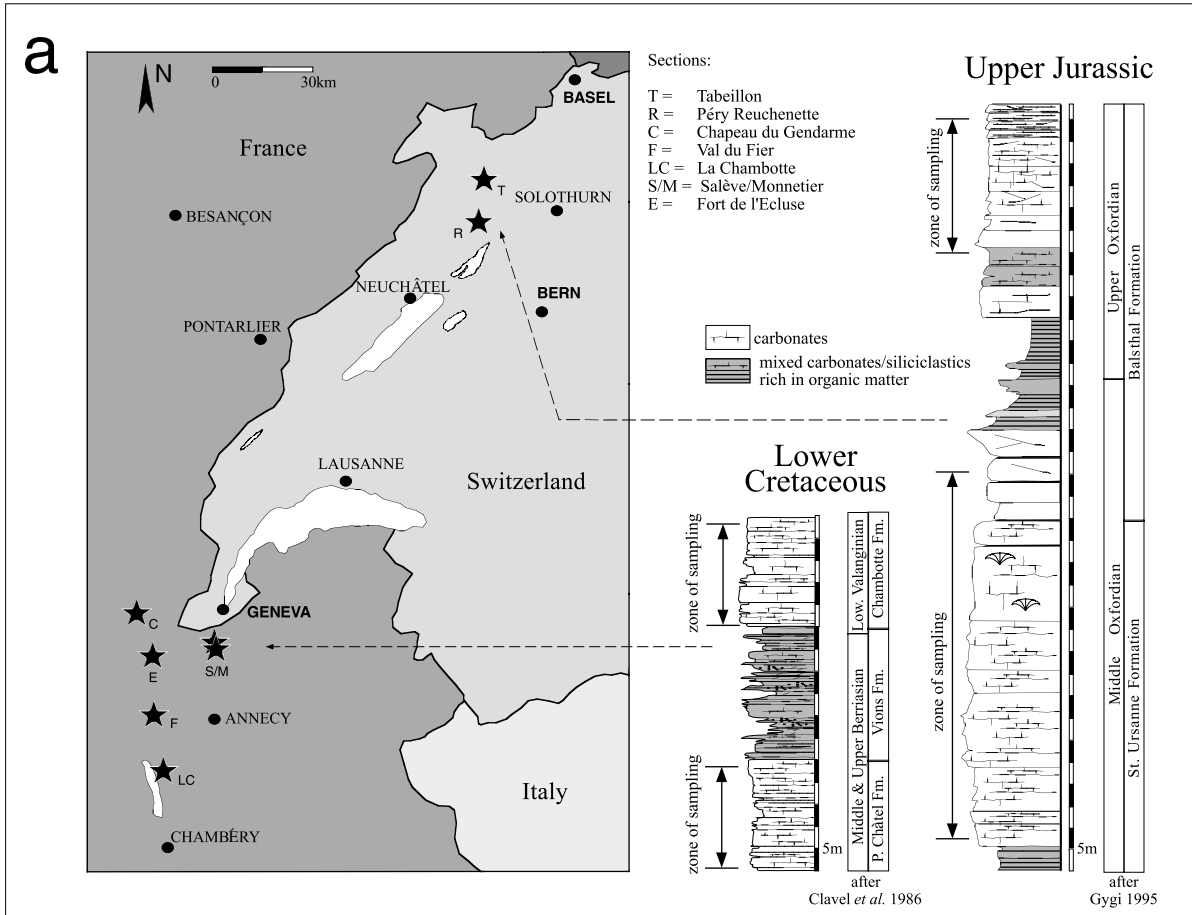


Fig. 1. Location of the study areas. (a) Lower Cretaceous and Upper Jurassic sections in the Swiss and French Jura Mountains. (b) Location of Wood Cay on the Bahama platform and characteristics of the subtidal ooid dunes.

STUDY AREAS

Sections of the Upper Jurassic (Middle/Upper Oxfordian) and Lower Cretaceous (Upper Berriasian/Lower Valanginian) in the Swiss and French Jura were examined (Fig. 1a). The sedimentary record mainly consists of protected lagoonal to high-energy perireefal carbonates and intercalated mixed carbonate-siliciclastic deposits with elevated contents of organic matter, frequent breaks in sedimentation and tidal influence. Discontinuity surfaces are expressed as abrupt facies changes and firm- to hardgrounds (Hillgärtner, 1998). In cases where such discontinuities occur in carbonate sands, 20 samples taken just below the surfaces locally show micritic envelopes around grains and binding of the grains by micritic 'meniscus-type' cements and filamentous textures.

Comparable fabrics occur in ooid sand waves in the vicinity of Wood Cay (one of the Schooner Cays), located on Eleuthera Bank ≈ 20 km to the west of the island of Eleuthera, Bahamas (Fig. 1b). Here, strong ebb-tidal currents form a set of large-scale climbing bedforms slowly migrating to the north-west. The sand waves have apparently never been subaerially exposed because, during neap tide, water depth was nowhere < 1 m. The sediment consists mainly of ooids and some skeletal fragments (foraminifera, green algae). Episodic currents and shallow water lead to a

low net accumulation of sediment. On the lower stoss side of the tidal bars and especially in the lee of the preceding crests, sediment is surficially stabilized by sea-grass (*Thalassia*) and green algae (*Udotea*, *Penicillus*, *Halimeda*). A sparse colonization by soft sponges (*Tedania*, *Spheciospongia*) and corals (*Manicina*, reworked but partially living *Porites*) is also present. Towards the crest of the sand waves, the sediment surface becomes progressively barren. In these areas, the sediment is stabilized by a patchy, firm crust of ≈ 1 – 2 cm thickness (Fig. 2). In places, the crust is covered by a layer of a few millimetres of loose grains. The crust and the environment of formation are similar to the 'subtidal algal mats' of Bathurst (1975) and the recent oolitic hardgrounds described by Dravis (1979). In contrast to the latter, however, the upper surface of the Wood Cay crust has not been visibly bored, corroded, abraded or encrusted by sessile organisms. It is therefore interpreted as firmground. Occasionally, *Callianassa* burrows penetrate and destroy the firm crust producing cohesive clasts that are subsequently reworked by currents. The resulting intraclasts are found on the tidal bars and in their surroundings (Fig. 2). Five samples taken from the firmground and several intraclasts were examined.

OBSERVATIONS

Mesozoic examples

Most of the Mesozoic samples were taken immediately below laterally continuous (10–500 m) discontinuity surfaces marking facies changes. Commonly, the facies change abruptly from high-energy lagoonal grainstones to lagoonal wacke-

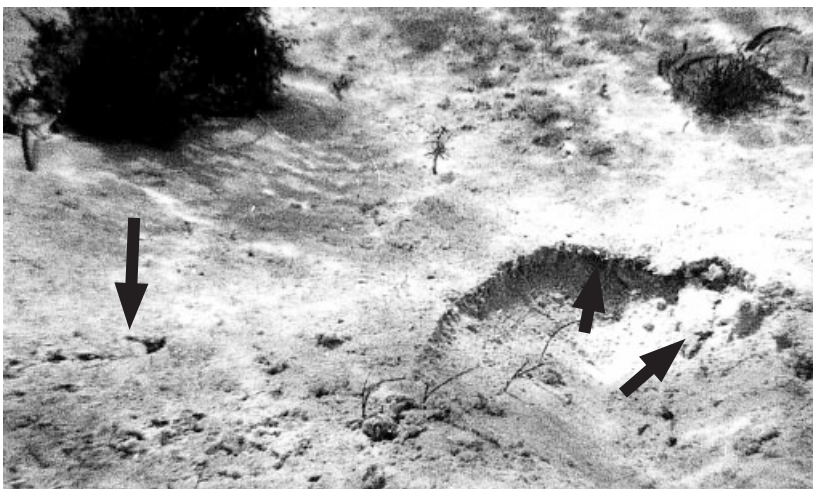


Fig. 2. Firmground on a subtidal bar near Wood Cay, Bahamas. The firm nature of a thin crust is seen at the rim of the artificially dug hole (short arrows). Diameter of the hole is 30 cm. Naturally reworked clasts of the crust are distributed on the surface (long arrow).

stones or marly mudstones. The sediments below the surface display minor biopenetration and/or bioturbation with well-preserved traces (commonly *Thalassinoides*), which are filled with the overlying sediments. In a few cases, surface encrustation by oysters, boring by lithophagids or, as in one case, initiation of reef growth occurs. Discontinuity surfaces therefore indicate lowering of accumulation rates and/or omission with stabilization and/or early cementation of the sediment. In cases in which high-energy lagoonal sedimentation continued above the surface, intraclasts of the sediment below testify to reworking of an incipiently lithified substrate. Possible hiatuses at the discontinuity surfaces cannot be quantified in absolute terms, because the breaks in sedimentation are below biostratigraphic resolution (Hillgärtner, 1998).

Micrite envelopes and meniscus cements

In most Mesozoic samples presented here, grains display crypto- to microcrystalline calcite envelopes, which range in thickness from 10 to 50 μm . Grain surfaces are commonly sharp and well preserved, suggesting that micrite envelopes are constructive (Fig. 3a). However, partial micritization may locally produce a transition from grain to envelope, and some grains show a penetrative darkening of the outer surface and formation of destructive micritic envelopes (Fig. 3b). In addition, grains are bound by crypto- to microcrystalline calcite preferentially near the grain contacts. These grain-to-grain bridges display a double-convex shape and resemble meniscus cements (e.g. Dunham, 1971; Meyers, 1987). Scanning electron microscope (SEM) analyses show no specific internal structure of the menisci (Fig. 3c and d), whereas a micropeloidal structure is occasionally visible in plane light (Fig. 3e). Micropeloids have diameters ranging from 15 μm to 50 μm . Micritic menisci display no significant differences in crystal forms compared with the grains they connect (Fig. 3c and d). The same is true for the concentration of elements such as Mg, S or Fe, which shows only negligible variations as revealed by EDS mapping of thin sections. Considering such homogeneity, recrystallization during late diagenesis probably affected the entire rock and evened out initial compositional differences, which occur during microbially stimulated carbonate precipitation (e.g. Beveridge & Fyfe, 1985).

The area where these micritic meniscus-type microfabrics occur is commonly a patchy, elonga-

ted zone from several millimetres up to a few centimetres in thickness, immediately underlying a sharp discontinuity surface. Reworked clasts, which may attain several centimetres in diameter and occur immediately above the surface, display the same microfabrics. Grains are commonly micritized at their outer rim, and pores are occluded by microcrystalline calcite (Fig. 3f). This suggests that the fabric had a stabilizing effect on the sediment surface and led to a rapid lithification. Thus, micritic grain-to-grain bridges can be viewed as early diagenetic cements. However, the stabilization of the sediment surface seems to have been limited to the uppermost zone only, near the sediment–water interface. The zone follows all irregularities of the surface and, in one particular sample, even lines a burrow penetrating down for about 2.5 cm (Fig. 4). Micritic envelopes and menisci gradually disappear away from the surface and, after 0.5–1 cm, the sediment appears to be completely free of this fabric (Fig. 4c).

These microfabrics occur in sediments where faunal composition (foraminifera, echinoderm fragments, ooids and other diverse bioclasts) and sedimentary structures (cross-bedding, lamination, bioturbation) suggest deposition in subtidal environments. Although micritic meniscus cements have been interpreted as indicators for marine vadose diagenesis (e.g. Harris *et al.*, 1985; Meyers, 1987; El Moursi & Montaggioni, 1994), no independent signs of early diagenesis in vadose environments were encountered in these samples.

Filamentous fabrics

In the same depositional environments and stratigraphic positions, filamentous fabrics also occur. Grains again display irregular micrite envelopes but, instead of menisci, micritic filaments are responsible for the binding (Fig. 5a). The filaments have thicknesses ranging from 20 to 50 μm . Two different types can be distinguished. One shows a small internal tube, surrounded by an irregular coat of microcrystalline calcite (Fig. 5a and b). The second type is thinner, relatively straight, microcrystalline and forms an intergranular cellular structure (Fig. 5c and d). All of these structures occur in a patchy to continuous layer several centimetres thick immediately below discontinuity surfaces.

Modern examples

Samples of the recent firmground near Wood Cay display fabrics similar to those encountered in the

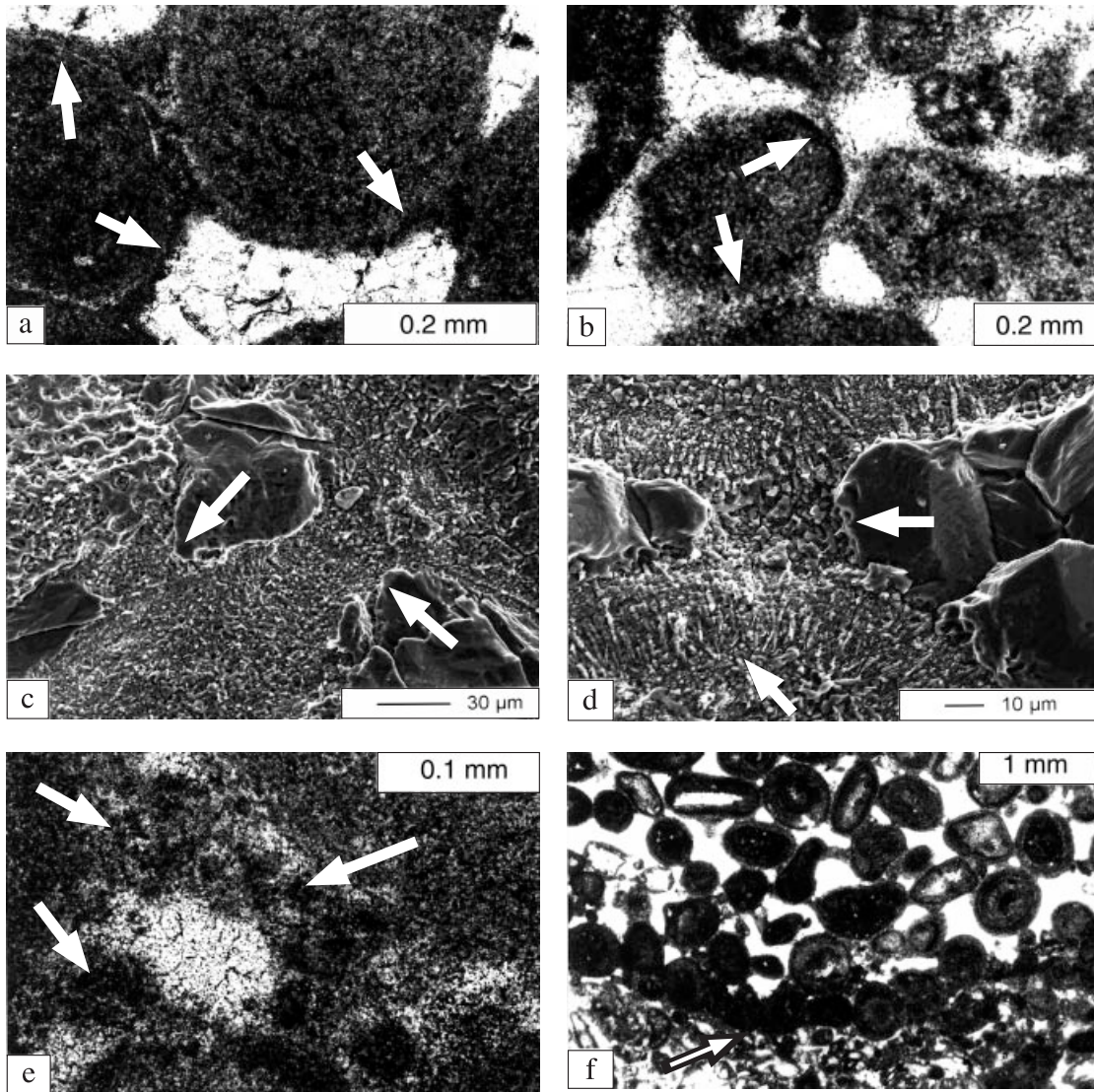


Fig. 3. Fabrics in Mesozoic firm- to hardgrounds. (a) Constructive micrite envelopes with a relatively sharp boundary between grains and envelope/meniscus-type cement (arrows). (b) Penetrative darkening of a grain and diffuse (micritized) boundary between grains and envelopes/meniscus-type cements. (c) and (d) SEM images of micritic meniscus-type cements. No specific microstructure is visible in the menisci (arrows), but concentric arrangement of crystals can be observed in the rims of ooids (lower arrow in d). (e) Micropeloidal structure of meniscus-type cements. (f) Reworked intraclast just above a firmground. Internally, the binding by meniscus-type cements is clearly visible, whereas the rim of the clast (arrow) is heavily micritized.

Mesozoic rocks. Cohesion between grains is caused by a combination of micrite envelopes, meniscus fabrics, acicular aragonite fringes and calcified filaments of epilithic and chasmolithic bacteria and/or fungi.

Micrite envelopes occur in two varieties. One has a diffuse character, and no clear boundary is visible between grain and envelope. Destructive micritization of the grain surface gradually passes into a slightly aggradational micritic envelope (Fig. 6a). The second type is a thin, dark micritic envelope partially surrounding grains.

Here, the grain–envelope contact is commonly sharp (Fig. 6b). An association of acicular aragonite fringes growing on the micrite envelopes is observed in patches throughout the firmground.

Calcified filaments, which bind the grains, are observed in great abundance in the firmground. These micritic filamentous structures attain thicknesses up to 50 μm and, when several filaments join, they form 100- to 150- μm -thick meniscus-shaped bridges between grains (Fig. 6c and d). In addition, such filaments can serve as

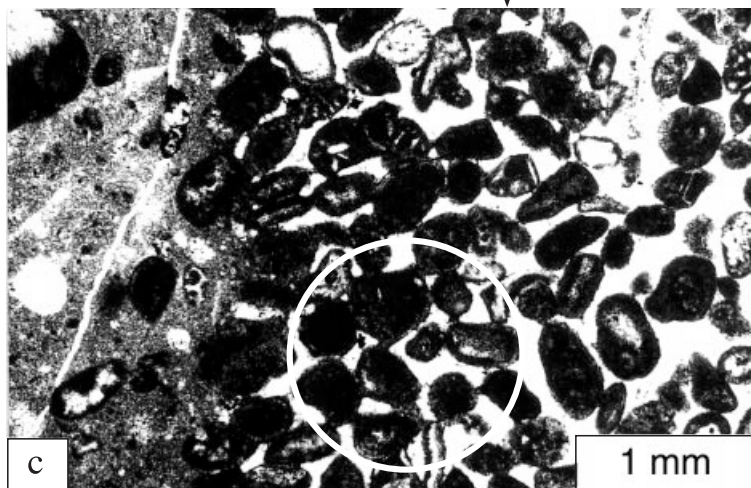
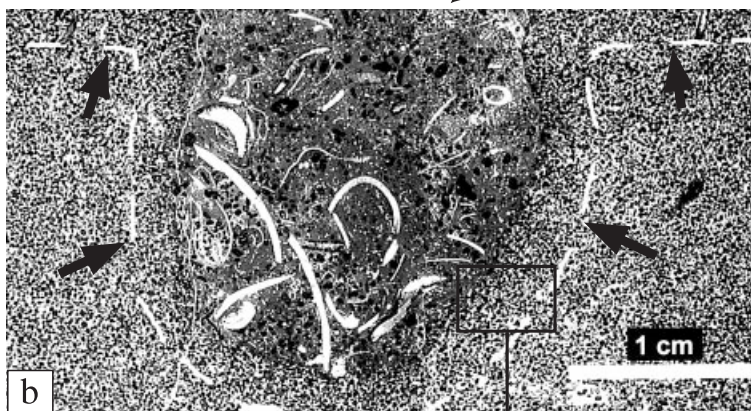
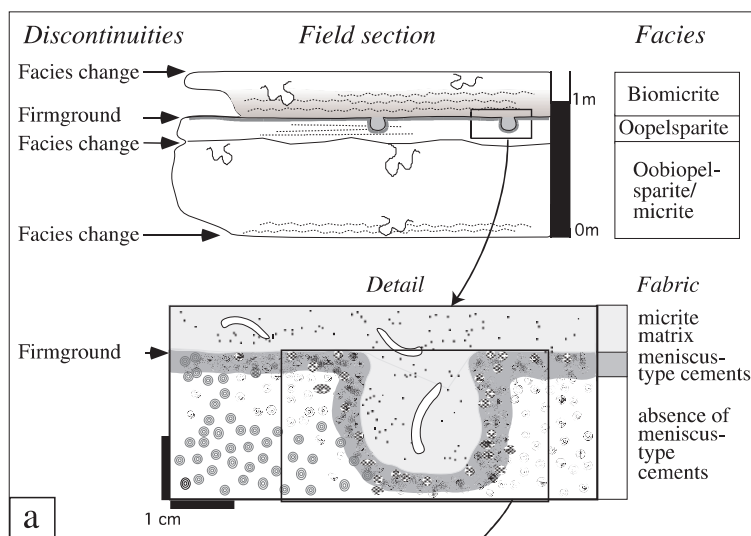


Fig. 4. (a) Representation of a firmground lined by an isopachous layer of meniscus-type cements. (b) Thin-section image of the firmground. The zone with meniscus-type cements lines all irregularities of the surface, including burrows penetrating for about 2.5 cm (dashed line and arrows). (c) Detail of (b) illustrating the microfabric of meniscus-type cements (circle). The density of the cements diminishes towards the right, away from the surface.

baffles for percolating micrite and small organisms (Fig. 6e). Micropeloidal structures within micrite bridges commonly occur together with intense endolithic activity and diffuse grain micritization (Fig. 6f).

Patches of acicular aragonite attached to grain surfaces are found repeatedly near grain contacts and in association with micritic filaments between grains (Fig. 6g). When such aragonite patches grow together, a meniscus-shaped cement

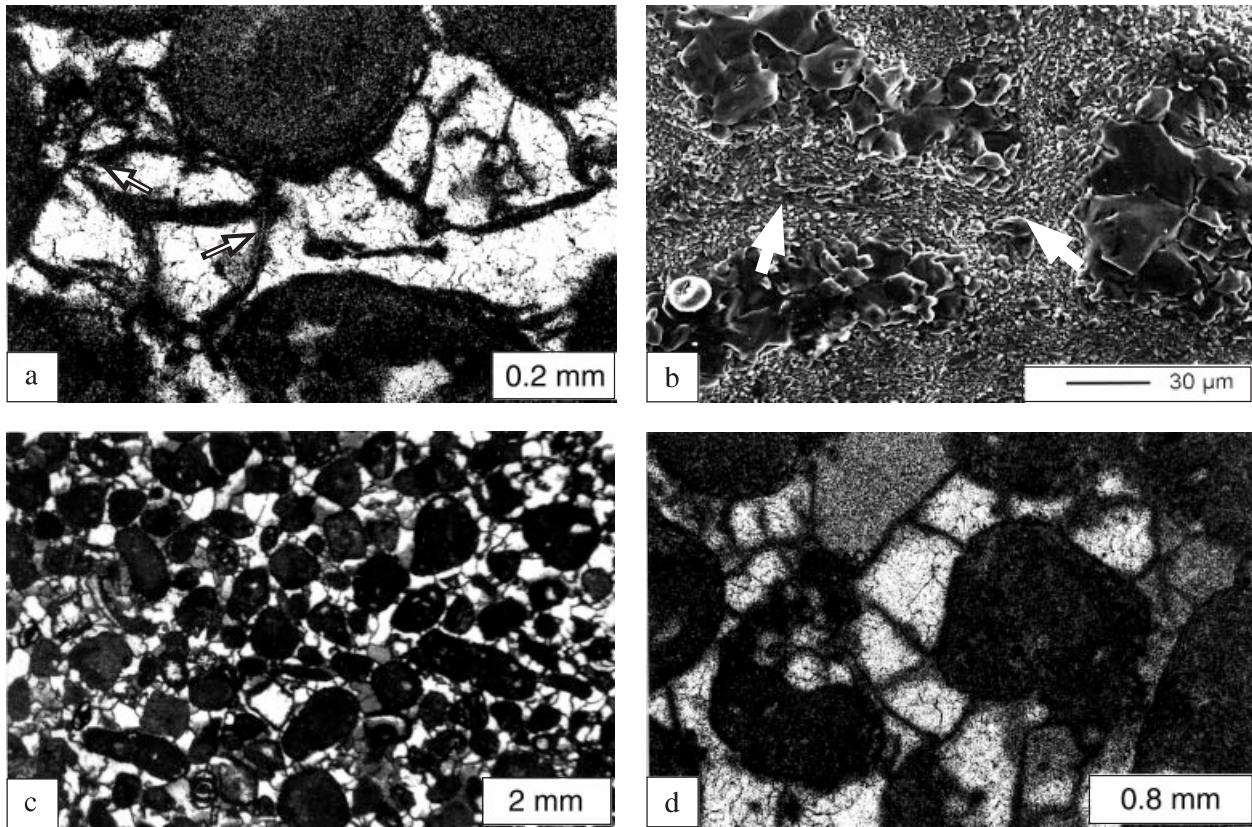


Fig. 5. Filamentous fabrics in Mesozoic firm- to hardgrounds. (a) Irregular micrite envelopes and filaments bind individual grains. Note the fine internal tubes in some filaments (arrows), probably representing voids left by decomposed organic filaments. (b) SEM image of grain-binding filaments. Calcite crystals in the filament interior have a more elongate shape and a different orientation from those at the outer rim (arrows), suggesting later replacement of an organic filament. (c) Grain binding by a network of chasmolithic filaments. (d) Detail of (c) showing the regular thickness and straight shape of the filaments. The cellular structure and micrite infill of single 'cells' strongly resembles the fabric of *Bacinella irregularis*.

is formed (Fig. 6h). One sample even displays a meniscus made up of sparry calcite with an internal structure resembling an organic filament (Fig. 6i).

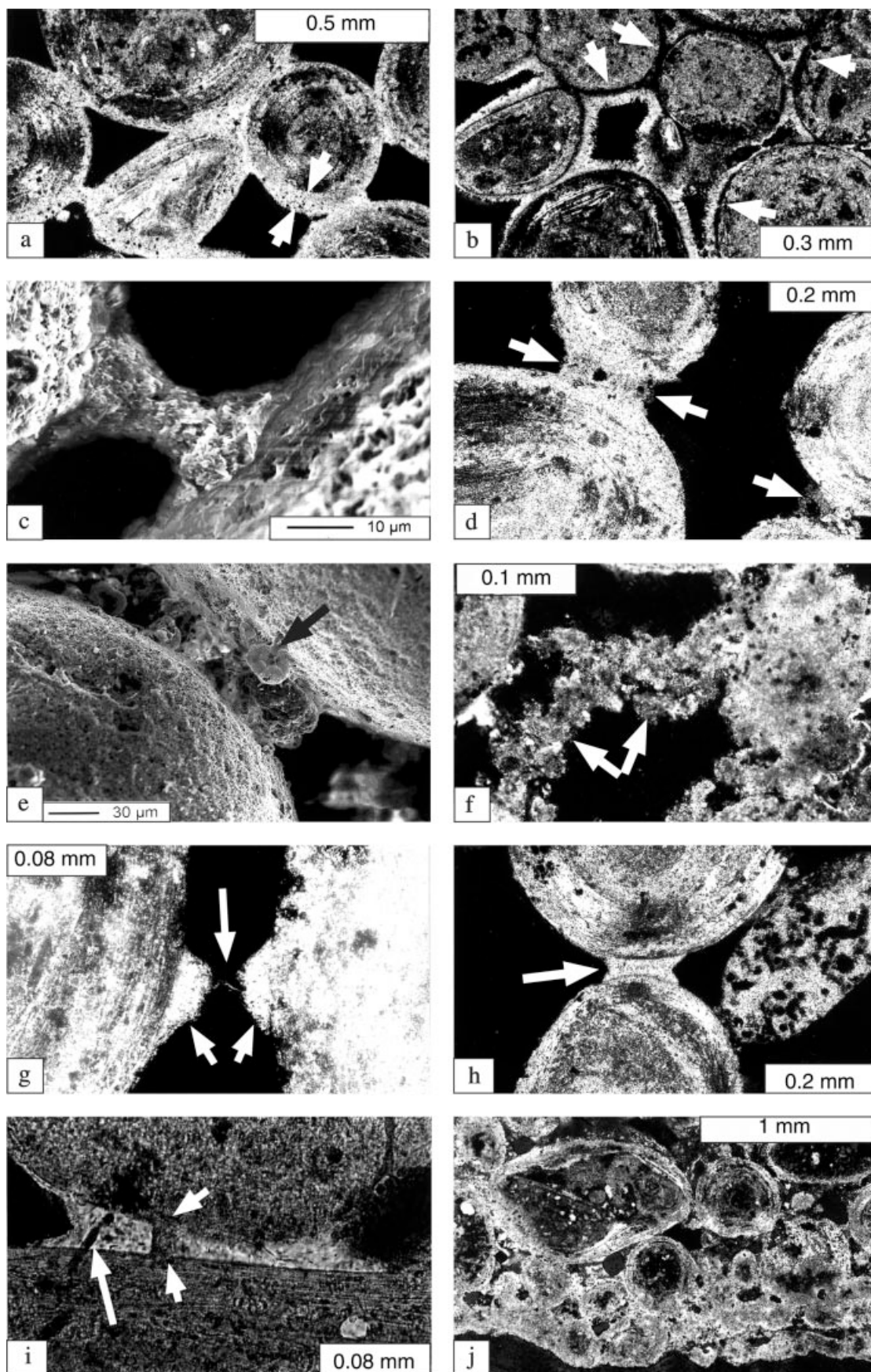
Reworked intraclasts of the firmground principally display the same fabrics. The outer rims of intraclasts, however, are intensively micritized, bored and cemented by calcified filaments and diffuse microspar (Fig. 6j).

DISCUSSION

Meniscus cements and micrite envelopes

The example of the modern firmground near Wood Cay demonstrates that micrite envelopes and meniscus-type cements can develop in subtidal conditions with low accumulation rates and variable energy conditions. Micrite envelopes that are observed in about 75% of the Mesozoic

Fig. 6. Fabrics in a recent firmground. (a) Ill-defined transition from micritized rims of grains to micrite envelopes/meniscus-type cements (between arrows). (b) Sharp boundaries between grains and micrite envelopes (arrows), which are preferentially overgrown by fibrous aragonite. (c) SEM image of microcrystalline aragonite, probably around a filament binding two grains. (d) Binding of grains by precipitation of micrite in a meniscus shape (arrows), probably around filaments. (e) Trapping of micrite and microorganisms (arrow) between grains. (f) Binding of grains by precipitation of micropeloidal micrite (arrows) and aragonite. (g) Fibrous aragonite preferentially precipitated where a thin filament (long arrow) is attached to the grain surfaces (short arrows). (h) Meniscus-shaped crystallization of fibrous aragonite (arrow) in the same sample. (i) High magnification of a sparitic, meniscus-shaped cement with an internal filament (short arrows) and a later boring (long arrow). (j) Outer rim of a reworked clast from the modern firmground collected on the surface of the tidal bar. Intense binding of grains by filaments and micrite precipitation. The outer rim is heavily micritized, and pores are occluded with micrite (compare with Fig. 3g).



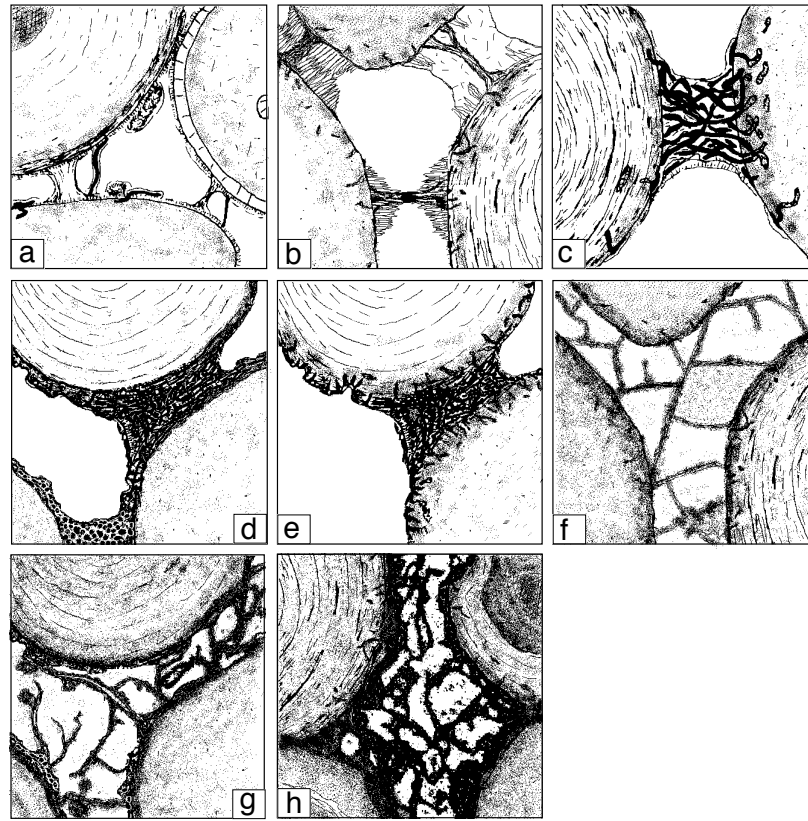


Fig. 7. Schematic representation of fabrics observed in modern and fossil firmgrounds and hardgrounds. (a) Threads of mucilage binding grains. (b) Preferential precipitation of aragonite/calcite around filaments forming meniscus-type grain bridges. Recrystallization of the aragonite or direct precipitation of calcite around a filament may lead to a sparitic meniscus (upper right). (c) Endomuocotic calcification of epilithic microbial filaments in a meniscus shape. (d) Constructive micrite envelopes and meniscus-type grain bridges. Microcrystalline aragonite or calcite precipitates in a pore-lining layer of organic mucus and an intertwined mesh of filaments of microbial epi- and chasmoliths. The micropeloidal structure (lower left) is typical of a microbial precipitate. (e) Micritic meniscus-type cement formed by microbially induced precipitation of micrite by non-filamentous microbes or by filamentous microbes without preservation of their organic structures. (f) Chasmolithic network of *Bacinella irregularis*. The filaments are regular in thickness and straight. Individual 'cells' filled with micrite are typical. (g) Calcified epi- and chasmolithic filaments of cyanobacterial or fungal origin extending from irregular micrite envelopes. (h) Alveolar septal fabric (added for comparative reasons, after a photomicrograph in Wright, 1986). Note the similarity to the filamentous fabric in (g). (Drawings a–c modified from Fabricius, 1977.)

samples show similar morphological evidence of microbial activity, such as irregular thickness with small protuberances and extending filamentous structures (Fig. 7; e.g. Kobluk & Risk, 1977a, b). Micropeloidal structures, which are commonly ascribed to bacterially induced precipitation of calcite (e.g. Chafetz, 1986; Chafetz & Buczynski, 1992), are observed in micrite envelopes and associated micritic meniscus-type grain-to-grain bridges, further suggesting a microbial origin for both fabrics.

Comparable fabrics are well known in grapestones (Taylor & Illing, 1969), which are aggregate grains formed in environments with low sedimentation rates and intermittent erosional events. Initially, sediment grains are coated by mucilage

and colonized by endo-, epi- and chasmolithic organisms such as cyanobacteria, fungi, bacteria, foraminifera, diatoms and polychaetes (Bathurst, 1975). They induce a loose binding that is followed by calcification of filaments and trapping of micrite. Micritic envelopes and meniscus-type bridges between grains are thus created (Winland & Matthews, 1974; Fabricius, 1977; Cros, 1979; Tucker & Wright, 1990, fig. 1.8). Most grapestones represent lithified remnants of reworked subtidal algal mats (e.g. Bathurst, 1975), and thus it can be assumed that such fabrics can be preserved along sediment surfaces that undergo sediment starvation and are not destroyed by erosion and/or bioturbation.

The association of micrite envelopes and micritic meniscus cements with discontinuity surfaces (firm- and hardgrounds) in the Mesozoic samples is significant. Purser (1969) has already described a strong positive correlation between pore-lining micrite envelopes and fossil hardgrounds. All of these surfaces lack any unequivocal features indicating subaerial exposure.

Direct evidence for a subtidal formation of these fabrics is difficult to obtain. However, in the case of the thin and isopachous band of meniscus cements lining a discontinuity (Fig. 4), a vadose origin seems very improbable. If capillary forces were the origin of the menisci, they should occur all the way down to a palaeogroundwater table and terminate along a more or less straight line, rather than following the palaeosurface. Dripstone cements indicating a vadose origin or sedimentary structures pointing to intertidal or supratidal exposure are not observed either. Therefore, in view of the evidence for a possible microbial origin of such fabrics, the surface in this sample is most probably a firmground that formed on a subtidal sand dune, where precipitation of micrite as a result of microbial activity stabilized the sediment.

Surfaces related to sediment starvation experience a concentration of biological activity and are prone to colonization by organisms. Intense pumping of water through the upper centimetres of porous sediments, mainly by wave action, can supply large amounts of organic matter to the interstitial microbial community (Shum & Sundby, 1996). There, it will be preferentially adsorbed around grains colonized by microbes (Mitterer & Cunningham, 1985). Microbial decomposition of this organic matter will then trigger the precipitation of calcite (see above). The question of why a fabric with meniscus-shaped grain-to-grain bridges is formed in subtidal settings can only be answered in a speculative way. Microbes will preferentially colonize the necks of the pores, where trapping of infiltrating organic matter and micrite-sized particles is most effective. The shorter distances between grains in the pore necks allow endolithic and/or epilithic microbes to bridge the gap from one grain to the next and, thus, they will be more abundant in these positions (Fig. 7). Consequently, microbially induced precipitation will be strongest there. The sea water pumped through the pores may additionally enhance a meniscus shape of such grain-to-grain bridges by an erosional rounding of the pores.

Fossil fabrics of microbial origin are generally micritic. In recent samples, however, fibrous aragonite and sparite in meniscus form occur around organic filaments (Figs 6c, d and 7). In this case, microbially induced microcrystalline precipitates may initially serve as nuclei for the growth of aragonite and/or calcite cements. Micrite envelopes, for example, are preferentially overgrown by fibrous aragonite (e.g. Strasser *et al.*, 1989). This is explained by favoured growth of aragonite crystals on microbially mediated calcite nuclei in grain-coating organic mucus (Taylor & Illing, 1969; Pierson & Shinn, 1985; Reitner, 1993). During later diagenesis, these cements may be recrystallized and/or micritized, the meniscus shape being preserved.

Meniscus-type grain-to-grain bridges are well known from vadose environments and can occur abundantly in the initial phases of calcretization, where grain-binding filamentous fabrics and uneven micrite envelopes gradually thicken and eventually occlude primary porosity (e.g. Calvet, 1982; Wright, 1986, 1994). The processes also involve microbial activity, and the resulting fabrics compare well with those described for grapestone formation and the observed subtidal fabrics. This demonstrates that micritic meniscus cements alone are not sufficient to identify an early diagenetic environment (Fig. 8). Other criteria, such as an association of sparitic menisci with pendant cements (Fig. 7) and structures such as root traces, are needed to demonstrate subaerial exposure and vadose conditions unequivocally.

Filamentous fabrics

Filamentous fabrics observed in the modern samples are clearly of biogenic origin. Various microorganisms, but mainly cyanobacteria and fungi, form epi- and chasolithic filaments in subtidal and vadose regimes. A detailed description and identification of the different species is beyond the scope of this paper. For more detailed information on filamentous microbes, see Kobluk & Risk (1977a, b) and Feldmann (1997) for subtidal environments and Kahle (1977), Klappa (1980), Calvet (1982), Wright (1986) and Phillips *et al.* (1987) for continental vadose settings.

Microfabrics in the Jurassic samples (Fig. 5a–d) are interpreted as a dense network of grain-binding filamentous chasoliths along subtidal firmgrounds. The variety with thin, straight filaments (Figs 5c, d and 7) sometimes occurs in association with *Lithocodium–Bacinella* oncoids

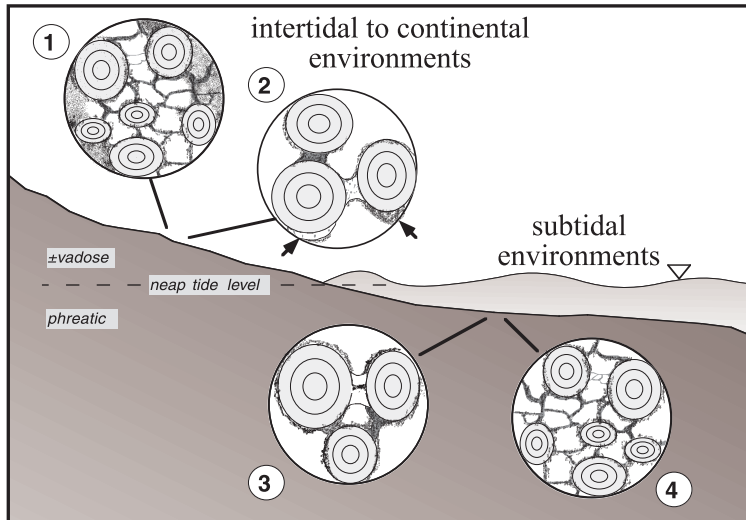


Fig. 8. Early diagenetic, microbially induced fabrics in different environmental settings. (1) Micritic (calcified) filaments and alveolar-septal structure. (2) Micrite envelopes, micritic and sparitic meniscus and pendant cements. Only a combination of these cement types can indicate a vadose diagenetic environment. (3) Micrite envelopes, micritic and fibrous (sparitic) meniscus-type cements. (4) Micritic filaments.

and, from its appearance, is a chasmolithic variety of *Bacinnella irregularis*. The diameter and the irregular outer rim of the filaments in the second variety (Figs 5a, b and 7) compare well with filaments in recent subtidal hardgrounds (Kobluk & Risk, 1977a, b; Dravis, 1979). Such epilithic and chasmolithic filaments commonly occur in combination with micrite envelopes and protrude into the pores. Such features can strongly resemble alveolar-septal structures described in palaeosols (Fig. 7; Calvet, 1982; Wright, 1986). Thus, here also care must be taken that additional evidence is considered to interpret palaeosol formation and subaerial exposure (Fig. 8).

ENVIRONMENTAL CONTROL

Active organic stabilization of sediment is well known in environments with filamentous microbial mats, which have the potential to trap and bind loose particles. In intertidal environments, the process of periodic sediment input and subsequent microbial stabilization of thin layers of mobile sediment can be very rapid. It takes only a few hours for organic filaments to penetrate completely and fix a 2-mm-thick layer of oolitic sand (Feldmann, 1997). However, in shallow marine and continental vadose environments, the active organic stabilization of carbonate sands through a diffuse chasmolithic colonization by filamentous microbes forms very fragile substrates that can easily be eroded and reworked without leaving any trace (e.g. Bathurst, 1975). Thus, environments favourable for such stabilization and preservation of such fabrics are

characterized by energy levels sufficiently strong constantly to remove mud-sized particles and add nutrients, but not strong enough constantly to displace sand-sized components. The main process of sediment stabilization, however, is the calcification of the microbial epilithic and chasmolithic filaments and organic mucus, and the formation of aragonite and calcite cements triggered thereby. Only these processes lead to the formation of more resistant substrates with preservation potential.

The most obvious factor influencing microbially induced carbonate precipitation appears to be the presence and abundance of organic matter (e.g. Webb *et al.*, 1999). Several environmental conditions, such as intermittent stability of the mobile sediment and low sediment accumulation rates, favour the concentration of organic matter and initial microbial colonization on a local scale. Many environmental variables on a regional to global scale may also play a role. Temperature, rainfall in the hinterland, $p\text{CO}_2$ and sea level influence terrigenous input and water saturation with carbonate and bicarbonate ions. This in turn influences the supply of organic matter and rates of abiotic and biotic carbonate precipitation (Riding, 1996).

It is important, however, to note that the presented examples of Mesozoic subtidal firm/hardgrounds in the Chambotte, St Ursanne and Upper Balsthal formations (Fig. 1a) occur in time intervals with a very low influx of terrigenous sediments and organic matter (Hillgärtner, 1999). During times with high inputs of siliciclastics and organic matter (e.g. Vions Formation, Fig. 1a), firm- and hardgrounds are even more abundant, but rarely show microbial fabrics (Hillgärtner,

1998). In contrast, they show intense bioturbation by *Thalassinoides*-producing organisms. Microbially influenced carbonate formation was certainly present during these times (abundant ooid and oncoid formation), but it seems that stabilization of sediment surfaces by microbial activity was either less common or not preserved. Higher nutrient levels probably favoured the activity of a variety of endobenthic organisms destroying any microbial fabrics. Good preservation of microbial fabrics (in general) seems to occur only in 'extreme' environments. They can be characterized by high-energy conditions and relatively low nutrient levels (this study), by high-mesotrophic conditions (abundance of organic matter/low O₂ levels) or by high salinities in which other benthic organisms are rare or cannot survive (Dupraz & Strasser, 1999). Initial stabilization and cementation of carbonate sands by microbial activity may be very common in subtidal environments, but characteristic fabrics will be preserved only under special environmental conditions, including low bioturbation, rapid burial and lithification of the discontinuity surface.

CONCLUSIONS

Recent and Mesozoic subtidal firmgrounds and hardgrounds in carbonate sands reveal a combination of early diagenetic features including micrite envelopes, filamentous fabrics and micritic meniscus-type cements. These fabrics appear to be the result of grain binding by microbial epi- and chasmolithic filaments, microbially induced calcification and trapping of percolating micritic sediment. A microbial origin is concluded on the basis of their morphological similarity to known filamentous microorganisms and internal micropeloidal structures, typically thought to be the result of microbially induced carbonate precipitation. Their occurrence in environments that are prone to microbial activity further strengthens this interpretation.

Stratigraphic condensation favours the accumulation of organic matter and benthic colonization of the substrate. In sand-sized sediments, organic matter impregnates the upper centimetres of the substrate and is concentrated in interstitial pores, especially near grain contacts where trapping is most effective. The presence and abundance of this organic matter is the main factor controlling heterotrophic metabolisms that stimulate carbonate precipitation in the absence of light. In addition, microbial filaments are preferential

sites for crystallization of aragonite and calcite near grain contacts. Consequently, it is concluded that microbial activity and associated processes, which have already been documented in grapestone formation, contribute to the cementation of subtidal carbonate sands and the formation of laterally continuous firm- and hardgrounds.

Morphologically, these subtidal fabrics are almost identical to fabrics observed in intertidal to vadose environments and fabrics described from continental vadose environments. Their strong resemblance is natural, because processes and factors controlling microbial activity are very similar in all these environments. In the Mesozoic examples, there are few, if any, opportunities to identify the different microorganisms involved. Possible diagnostic differences in mineralogy and the microstructure of crystals are probably obliterated by later diagenesis. This has consequences for the interpretation of early diagenetic environments based on sediment fabrics:

1. Micritic meniscus cements should not be taken as a sole indicator of vadose diagenesis. To differentiate micritic cements with a meniscus shape from sparitic, vadose meniscus cements, the former should be called 'meniscus-type cements'. Although quantitatively insignificant, it appears that, even in subtidal environments, microbial filaments may trigger sparitic aragonite and calcite precipitation in the form of menisci.
2. The resemblance of many filamentous fabrics in subtidal environments to alveolar septal texture described in calcretes and palaeosols indicates that these structures also should not be used as sole evidence for subaerial exposure.

The fact that only a few Mesozoic, subtidal firm- and hardgrounds in sandy substrates show such fabrics probably results from the low preservation potential of these delicate structures, mainly because of abundant bioturbation at omission surfaces.

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