Diversity of Bahamian Microbialite Substrates

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Abstract Stromatolites, laminated columnar and branched structures of limestone and dolomite, are the only macroscopic evidence of life for the first few billion years of earth history. These organo-sedimentary structures are a prominent constituent of Precambrian carbonate successions and occur sporadically throughout the Phanerozoic. They are hosts for metallic ores and serve as reservoir rocks for hydrocarbons. Still living Bahamian columnar forms that are counterparts of ancient microbialites (stromatolitic and thrombolitic) provide a special opportunity to examine if their substrates played a role in determining the occurrences and patterns of these remarkable structures. The cyanobacterial builders of Bahamian stromatolites can colonize almost all substrates except mobile sands. The development of columnar structures with significant relief however, requires either a hard or firm substrate. From published reports on substrates and our own observations we recognize two families of substrates: inherited, consisting of pre-existing rock surfaces and renewable, including all substrates that can develop repeatedly during accumulation. Inherited substrates in the Bahamas include Pleistocene limestone with or without palimpsest encrustations of caliche or paleosol. Renewable substrates in the marine environment include syndepositional hardgrouds, large skeletons of corals and mollusks, encrustations of coralline algae or vermetid gastropods, and firm grounds of fine-grained carbonate sediment. Recognizing the key roles of renewable substrates in determining the occurrences and age variations of modern Bahamian specimens emphasizes the need for increased attention to the foundations of microbialites in future studies.

1 Introduction

Stromatolites are laminated, lithified columnar, branched, and hemispheroidal structures that accrete from a single point (Semikhatov et al. 1979). They are a major component of carbonate platforms in the Precambrian and sporadically throughout

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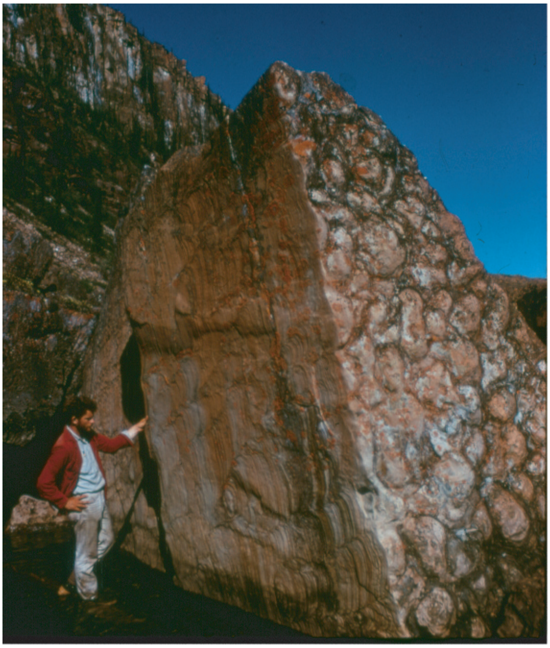

Fig. 1 Example of classic Precambrian stromatolites, Pethei Group, Great Slave Lake, NWT, Canada. The large slumped slab shows the columnar growth form (in plan view) and the characteristic convex-upward laminations (in cross sectional view). Photo Paul Hoffman

the Phanerozoic (Fig. 1). Stromatolites form through the dynamic interactions of a microbial community, geochemical reactions, and local sedimentation. Cyanobacteria are the predominant element of benthic communities forming nearly all modern stromatolites and were most probably also the builders of the majority of their fossil counterparts.

The cyanobacterial builders of stromatolites are ever-present on the earth's surface: hot springs, polar ice, terrestrial environments, fresh and hypersaline waters, and are likely some of the most abundant life forms in the oceans (Waterbury et al. 1979). When many species of cyanobacteria encounter a stable substrate, they attach, multiply and spread to form a benthic community. Cyanobacterially-dominated benthic microbial communities are complex associations of photosynthetic and heterotrophic bacteria (Monty 1976; Papineau et al. 2005). Transforming a prostrate microbial mat into a microbialite rising above the surroundings requires building materials. Luckily, two sources have long been available. One is sediment trapped and firmly bound by the agile bacteria. The other building material, which is predominate in early Precambrian stromatolites, is calcium carbonate precipitated like plaster on or within the microbial mat. This carbonate precipitation in many extant stromatolites is triggered by the metabolic activities of the benthic microbial community, a topic that has been extensively studied. Within the benthic microbial community, cyanobacterial photosynthesis can locally lower the carbon dioxide concentration, which raises the pH and induces carbonate precipitation. Organic matter remineralization, predominately through sulfate reduction, can also promote carbonate precipitation (For recent reviews see Andres et al. 2006; Arp et al. 1999, 2003; Visscher et al. 2000; Visscher et al. 1998). Whichever of these two building materials is used, the formation of single lamina must be repeated to build a structure rising above its surroundings. This repetition can be caused by cyanobacteria motility, recolonization of the growth surface, variation in the types of benthic communities, or periodicity in the accretion linked to a dynamic environment (Monty 1976; Reid et al. 2000). The end result of repeated laminae of sediment or precipitated carbonate are structures composed of convex-upward laminations—stromatolites (Fig. 1).

2 Discovery and Significances of Holocene Stromatolites

When stromatolites were first discovered, late 19th and early 20th century, paleontologists and sedimentary geologists were baffled by these non-skeletal laminated domes and columns. There was longstanding debate if these layered structures they were animal, plant or purely mineral.

One of the early breakthroughs in understanding the origins of stromatolites came in the 1930s when an adventurous young Englishman named Maurice Black traversed the shallow lakes and swamps of Andros Island, Bahamas by canoe. His paper (Black 1933) described how self-replicating cyanobacterial mats alternating with periodic deposition of sediment could produce unlithified laminated structures resembling ancient stromatolites.

The discovery of well-lithified marine stromatolites, first in a hyper-saline lagoon in Shark Bay in Western Australia (Fig. 2) (Logan 1961; Playford and Cockbain

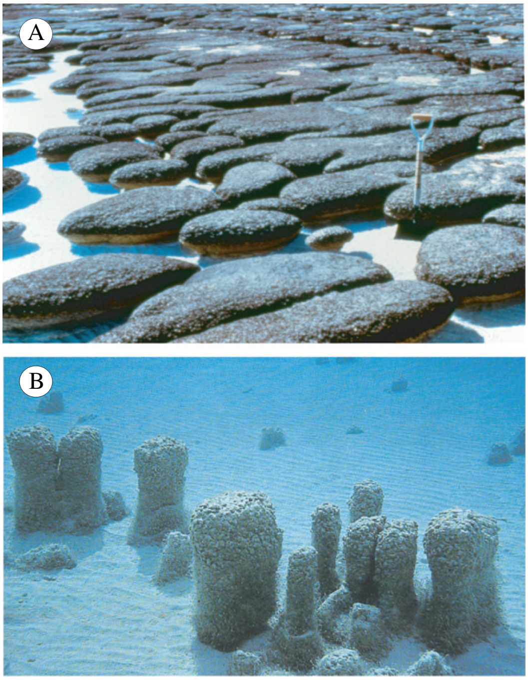

Fig. 2 Shark Bay stromatolites, Western Australia. (**A**) Exposed, wave-trained and elongated stromatolites. Photograph B. Logan. (**B**) Subtidal columnar stromatolites of variable heights. The tallest stromatolites in photo are 40 cm. Photograph P. Playford

1976) and more recently in tidal channels of the Bahamas (Dill et al. 1986; Dravis 1983; Reid et al. 1995)(Fig. 3), inspired seminal research on microbial carbonates. For example, detailed research on intertidal stromatolites in the Bahamas added novel concepts about stromatolite laminae formation (Andres, Sumner, Reid and Swart 2006; Browne et al. 2000; Macintyre et al. 2000; Reid et al. 2000; Visscher et al. 2000).

The Bahamian stromatolites are of special relevance to interpreting fossil examples. They develop in subtidal settings of up to 10 m deep in waters of oceanic salinities (35–37 ppt) (Dill et al. 1986). The Bahamian stromatolites, therefore, form

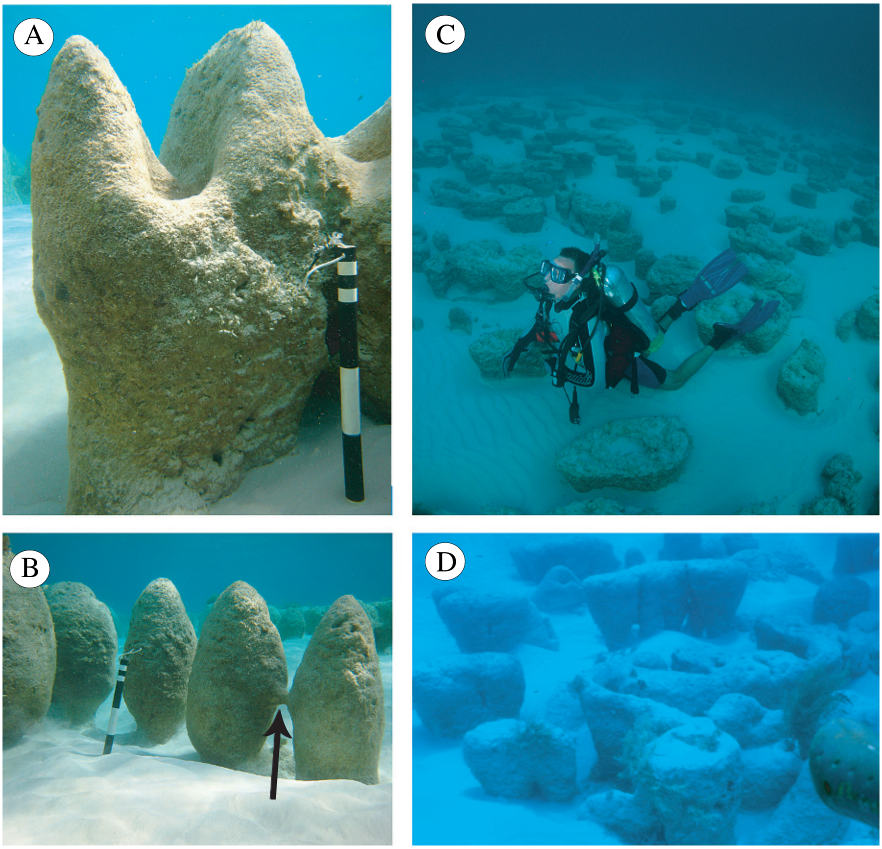

Fig. 3 Underwater views of diverse morphologies of Bahamian microbialites. (**A**) Microbialite with two conical projections—either branched or two ovoids fused by cemented sand when buried. Bock Cay, depth ∼ 4 m. Scale divisions 2 and 10 cm. (**B**) A row of ovoid microbialites with two bridged by cemented sand (arrow). Scale divisions 2 and 10 cm. (**C**) Underwater view of Adderly Channel floor, depth ∼ 5 m, with abundant mostly individual microbialites. (**D**) A varied cluster of microbialites in Adderly Channel, ∼ 6 m deep, The three specimens at top are fused together; so are the two at lower left partly buried in sand. The central microbialite appears to be compound

in a sedimentological setting that can be more directly related to the marine fossil examples than other modern analogues, such as the relatively common modern lacustrine stromatolites. Further, the Bahamian stromatolites are morphologically variable (Fig. 3) and occur as columns up to two meters tall, characteristics common in Precambrian, but rare in most modern stromatolites.

The most extensive and well-cemented Bahamian stromatolites are found in the tidal channels of the Exuma Islands, notably in Adderly Channel (Figs. 4 and 5). Lithified stromatolites also occur in the intertidal zone of these islands (Fig. 4). We have recently discovered stromatolites in the large apron of ooid shoals around the Tongue of the Ocean (Fig. 4). For unknown reasons they have not been detected on ooid shoals in the Western Bahamas or on Little Bahama Bank. The Bahamian microbial structures were initially described as stromatolites (Dill et al. 1986; Dravis 1983; Reid et al. 1995). Some of these specimens lack laminations but have clotted fabrics and have been termed thrombolites (Browne et al. 2000; Dill 1991; Feldman and McKenzie 1998). Additionally, both lithified and unlithified laminated microbial structures are widespread in peritidal sediments, especially on the extensive tidal flats of Andros Island (Fig. 4) (Monty 1976). These varied settings provide a special opportunity to consider two key elements of stromatolite construction: the variety of substrates and the supply of building materials. We are fortunate that our predecessors' research on these elements and their physical environment provides a thorough foundation of information and analysis. Our research over two field seasons provides significant additional data.

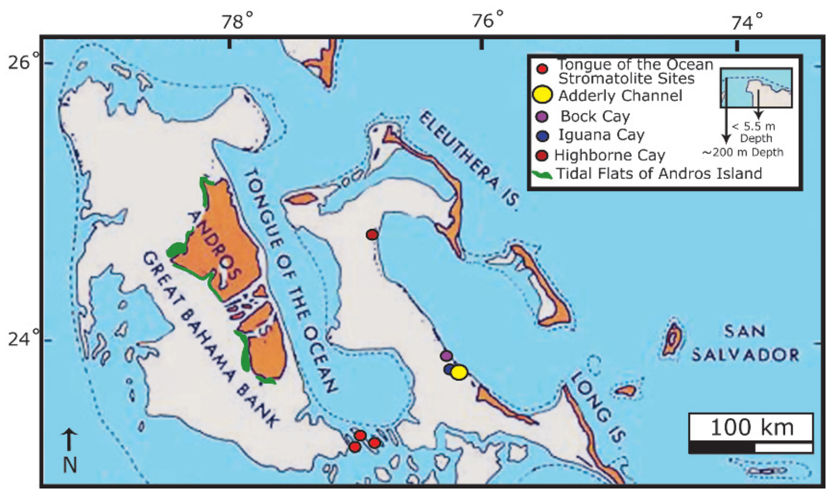

Fig. 4 Map of examined Bahamian stromatolites and peritidal microbial mats localities. The stromatolites are all occur on the shallow banks between sand wavers at depths of <10 m. Several stromatolites localities are in the tidal channels along a thin string of Pleistocene island, the Exumas. Modified from map by Chris Kendall

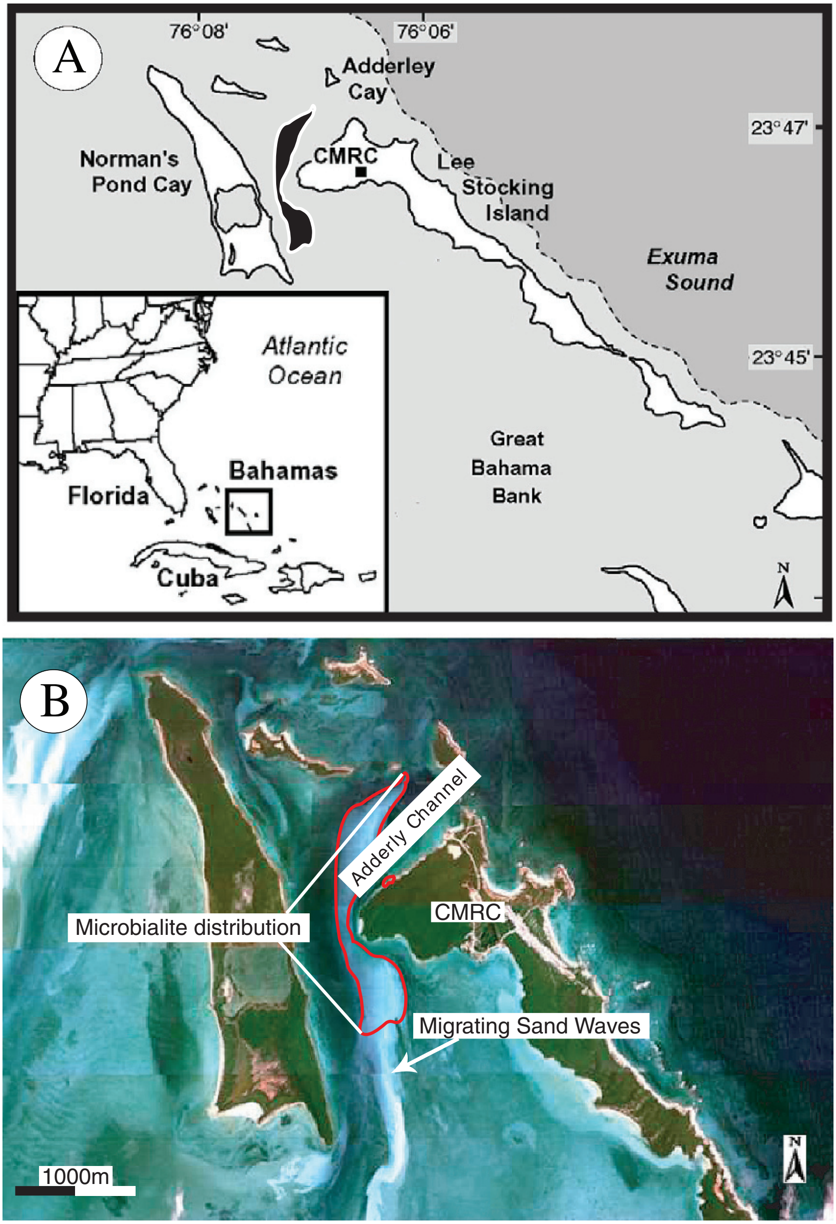

Fig. 5 (**A**) Detail of the depositional setting of Adderly Channel near Lee Stocking area, Exuma Islands. The blackened area outlines a sand bar in the Adderly tidal channel, the site of imaged and studied microbialites substrates. Modified from (Hu and Burdige 2007). (**B**) Aerial photograph of Adderly Channel showing the mid-channel sand bar and extent of microbialites. The sand bar varies from 5–7 m below sea level, and it is ornamented by sand waves up to ∼2 m high oriented at high angles to the bar trend. The sand waves are moved by the twice-daily tidal currents and periodically cover and uncover the microbialites. CRMC is the Caribbean Marine Research Center

3 Types of Holocene Substrates

We found two main classes of substrates, those that are pre-existing rock surfaces, here termed (1) inherited, and those that are developed repeatedly by sedimentary processes, here termed (2) renewable substrates.

3.1 Inherited Substrates

There have been detailed descriptions of inherited substrates of Holocene stromatolites. From his extensive observations of the Adderly Channel stromatolites Dill [1991] concluded that the stromatolites grew on "...either rubble hard-ground or caliche-encrusted paleosol." The paleosol overlies Pleistocene coral heads whose partial dissolution is usually considered evidence of subaerial exposure. Shapiro and others described four short diamond cores of the substrate of an area of stromatolites near Iguana Key less than a few kilometers from Adderly Channel. The stromatolites developed either on Pleistocene eolianite with rhizomorphs or early Holocene coral skeletons. In addition to these known examples, our diamond coring in Adderly Channel in 2006 recovered well-cemented limestone with features characteristic of subaerial exposure of Pleistocene limestone (for example blackened surfaces and black pebbles (Pierson and Shinn 1983)) below four different areas of stromatolites.

3.2 Renewable Substrates

We found stromatolites growing on several previously undocumented types of substrates that can form syndepositional. These renewable substrates include submarine hardgrounds, large mollusk shells, conglomerates composed of intraclasts, and firmgrounds.

3.3 Submarine Hardgrounds

Submarine hardgrounds have been described from several areas on the Bahama Bank. For example, there are well-documented hardgrounds from Yellow Bank (Taft et al. 1968) and the northern margin of Tongue of the Ocean (Palmer 1979) We recently discovered hardgrounds across a wide area in the southwestern section of the ooid shoals around the Tongue of the Ocean (Fig. 6). These locally extensive hardgrounds are formed by penecontemporaneous deposition of fibrous aragonite between sand grains (Fig. 6C–F). This same type of cementation is present in intertidal beachrock (for example, Gischler and Lomando 1997). Most hardgrounds on the Bahama bank have undergone some degree of early diagenetic alteration, after which the fibrous cement morphology is not easily distinguishable (Fig. 6D). This early diagenetic process further stabilizes the sediment. The cementation is usually

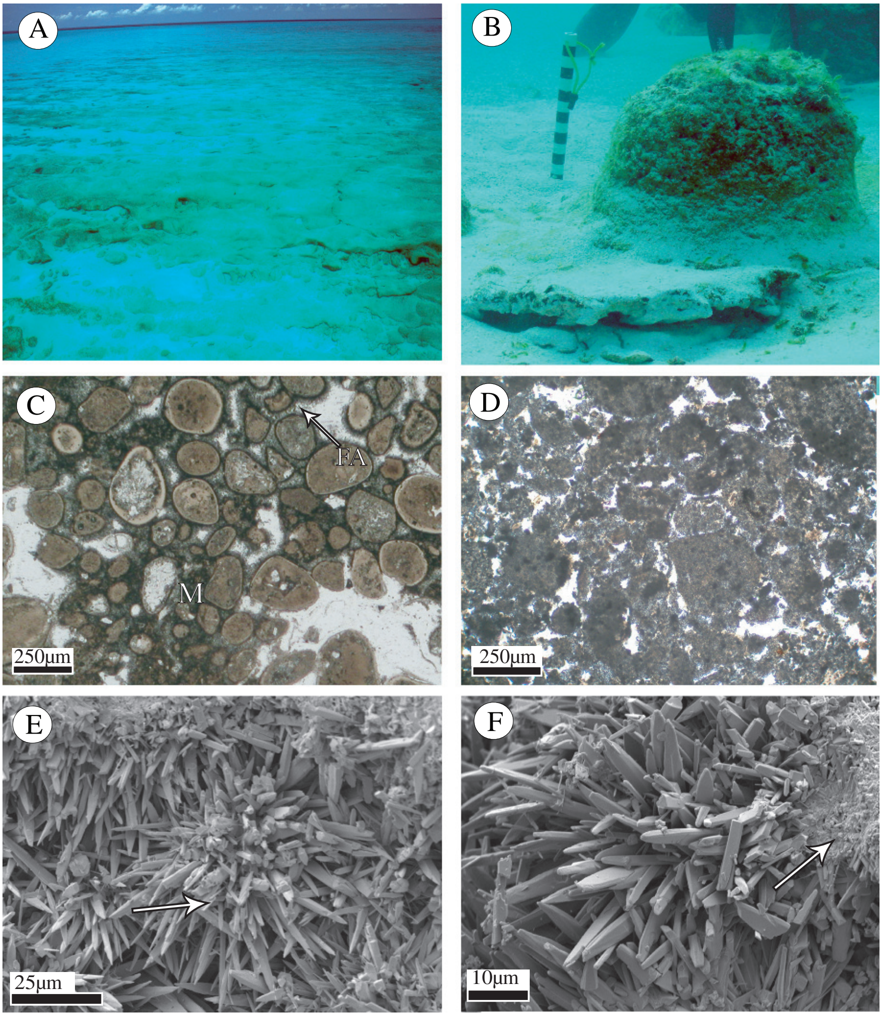

Fig. 6 Images of submarine hardgrounds, their microfabrics and microbialites. (**A**) View from the deck of our research vessel. R/V Tiburon three meters above the sea surface of a hardground pavement at ~2 m depth on an ooid sand shoal, Tongue of the Ocean (Fig. 4). The pavement extends for hundreds of meters, it cracks and breaks up to form intraclasts of varied sizes as seen in the foreground. (**B**). A small domal microbialite growing on a thin submarine hardground on an ooid sand shoal at a depth of ~2.5 m, Tongue of the Ocean (Fig. 4) Scale divisions 5 cm. (**C**) Examples of micritic (M) and fibrous aragonite (FA) as intergranular cements. Photomicrograph in plain polarized light. (**D**) Another fabric present in hardgrounds composed of peloids modified by early diagenetic recrystallization probably through a combination of local dissolution/reprecipitation and cyanobacterial boring. Grain boundaries are indistinct or jagged in the micritized areas. Photomicrograph in plain polarized light. (**E**) SEM image of spherulitic fibrous aragonite cement (arrow) that initiated from surrounding sand grains. (**F**) Higher magnification SEM image of fibrous aragonite cement growing on an initial micrite cement (arrow)

limited to layers of calcareous sand < 20 cm thick. These relatively thin layers of rock that are underlain by uncemented sand are mechanically unstable. They develop cracks, which in turn produce various sized interclasts (Fig. 6A). Multiple layers of hard-grounds are present in the Holocene sediments of eastern Great Bahama Bank (Palmer 1979). We have indicating that their formation is repeated. We have discovered several examples of stromatolites growing on submarine hardgrounds, including several stromatolites in the on shallow sand bars around the south end of the Tongue of the Ocean (Fig. 6B) and from the base of a giant stromatolite near Iguana Cay.

3.4 Interclasts and other Renewable Substrates

Shells of mollusks especially those of the large gastropod (*Strombus gigas*) litter many tidal channels and are large enough to provide stable substrate for small stromatolites (Fig. 7A). A shell that is the base of a small stromatolite (comparable to that of Fig. 7A) had a corrected ^{14}C age of 480±50 years (Dill et al. 1986). Clusters of cobble sized fragments of mollusks and corals intermixed with intraclasts, and locally enhanced by inter-particle cementation, can also provide stable substrates

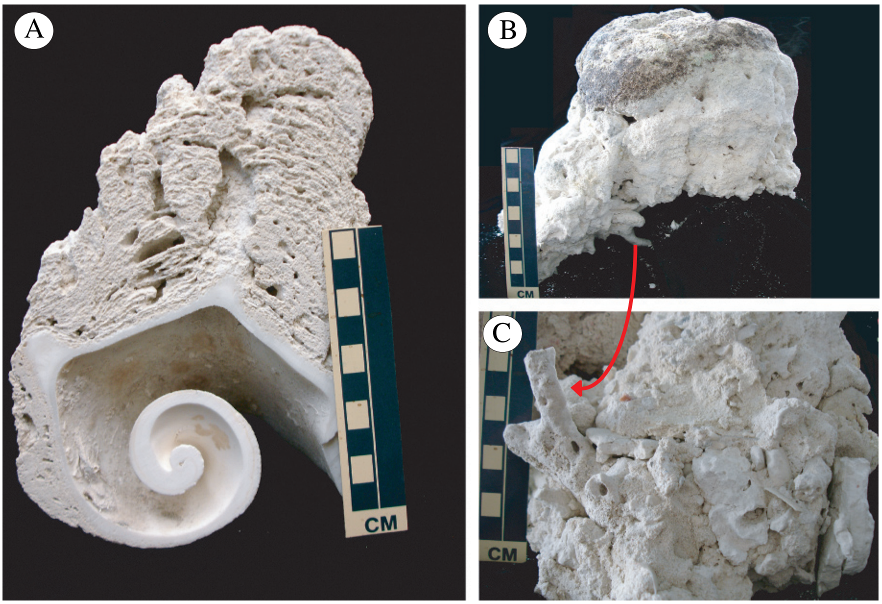

Fig. 7 Two examples of renewable substrates from Adderly Channel Depth range 5–7 m. (**A**) Cross section of a small stromatolite developed on a conch shell. (**B**) A small stromatolite on a conglomerate substrate. Scale divisions are 1 cm. (**C**) View of the underside of the specimen shown in B revealing that it is a composed of intraclasts of fine-grained sediment and metazoan debris

for microbialites (Fig. 7B and C). The variable degree of rounding of these clasts, their large grain sizes (> 5 cm), and their localized occurrence suggests they are storm deposits.

The substrates of intertidal occurrences of stromatolites appear to be quite different from the subtidal examples described above. On Stocking Island stromatolitic buildups of up to a meter thick grew on cemented branched coralline algae and vermetid gastropods that over lies Pleistocene limestone (Macintyre et al. 1996). The cements are magnesium-calcite and fibrous aragonite, indicating marine, rather than meteoric, deposition. At the Highborne Cay locality, the substrate of back reef stromatolites and "thrombolites" (Reid et al. 1999) consists of an unusual grain-free micrite composed largely of "filament moulds, 3–10 μm encased in spherulitic clusters of aragonite needles." (Reid et al. 1999). The substrates of both these two localities are products of penecontemporaneous cementation.

3.5 Firmgrounds

The firm-grounds that are renewable substrates for stromatolites in Adderly Channel are remarkable deposits (Fig. 8). Their occurrences and microstructure were thoroughly described and illustrated by Dill [1991], who termed them mud beds because of their softness and sticky feel. Dill [1991] and Shinn and co-authors (Shinn et al. 1993) reported that these laminated sediments are commonly about 10 cm thick and occur at depths of 4–8 m below sea level in the troughs between migrating sand waves (Fig. 8B) (Shinn et al. 1993). There they are underlain and overlain by ooid and/or peloid sand. These pure white sediments are soft but cohesive enough to break between the fingers with angular fractures. Intraclasts of the firmgrounds are abundant. Fragments of sea grass blades, wood, mangrove leaves, and palmetto fronds along with shells were commonly found within the laminations. The firmgrounds are composed of small argonite needles, which are often clumped together to form peloids around to 60 μm in diameter (Fig. 9B).

Dill [1991] proposed that these fine-grained laminated sediments containing terrestrially derived material were deposited during and following hurricanes when fine sediment suspended by storm waves settled from suspension. Confirmation of this interpretation came from a study of the deposits of Hurricane Andrew in 1992 (Shinn et al. 1993). This storm crossed the Joulters Cays, an area of ooid sands on northern Great Bahama Bank that has been studied extensively. There, soon after Hurricane Andrew, Shinn and co-authors (*ibid*) colleagues found firmgrounds and intraclasts of fine-grained sediment in tidal channels of ooid sands. The firmgrounds consisted of peloids 50–100 μm and some skeletal fragments sandwiched between uncemented ooid sand. These peloids, like those in Adderly Channel, consist of needle-shaped crystals of aragonite 1–3 μm (Fig. 9A). The use of mud in describing these sediments led to the interpretation that they accumulated by settling from suspension. The prevalence of laminated fine-sand

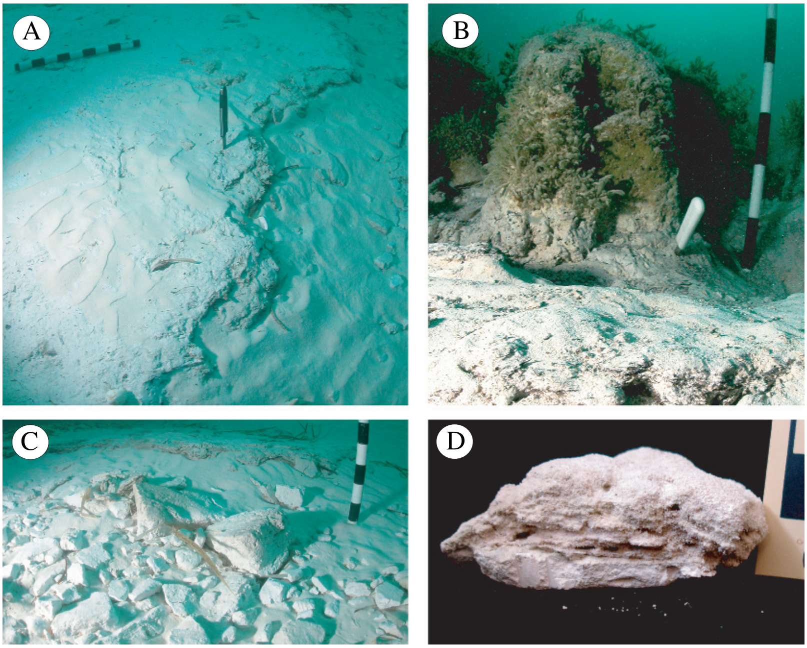

Fig. 8 Subtidal firm-ground substrates from Adderly Channel. (**A**) Example of an extensive layer of the firm-grounds, the "mud beds" of Dill [1991], from approximately six meters depth. Scale divisions 10 cm. Current erosion of the margin produces intraclasts as seen in **C**. (**B**) A small columnar stromatolite now covered with algae (*Batophora spp.*) that grew on a firmground like that in (a) exposed in the foreground. Scale division 10 cm, depth 7 m. (**C**) A local concentration of intraclasts produced by erosion shown in (**A**) depth 6 m. (**D**) A small stromatolite developed on a firmground like that in (Fig. 8A), depth 7 m; black scale bar 1 cm

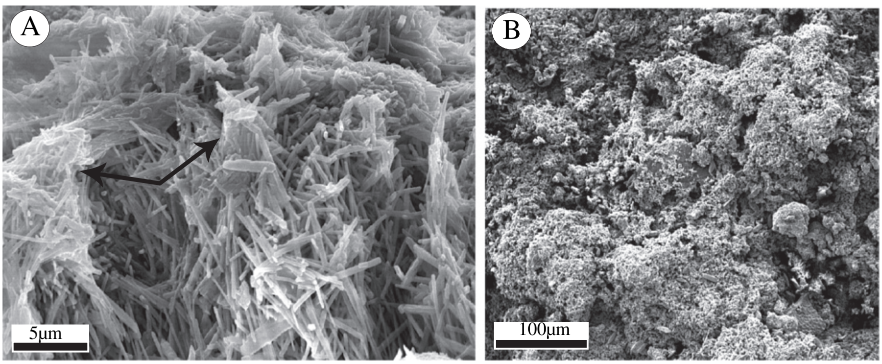

Fig. 9 Microstructure of the firmground substrate. (**A**) SEM image of fibrous aragonite from the firmground (Fig. 8A), (**B**) SEM image showing that the fibrous aragonite in Figure 8A occurs in semi-spherical clusters from 20 to 100 µm in diameter that are probably peloids

sized peloids, however, is more likely evidence that they are traction deposits in which soft but coherent peloids were sorted by bottom currents to produce the laminations.

Cementation and early diagenetic alteration of aragonite fibers increases the stability of the firmground sediment. When exposed to seawater the surfaces especially those of intraclasts “become encrusted with millimeter-thick, marine-carbonate cement”(Dill et al. 1986). We have found that this cement consists of intergrown aragonite fibers up to several microns long and 0.1 microns in diameter (Fig. 9A) oriented tangentially to the exposed surfaces. The aragonite fibers within the firmground are often fused together suggesting that penecontemporaneous recrystallization contributes to their coherence. Compaction dewatering may also have some affect on crystal morphology and packing. Together all these processes within the original firmground sediment lead to its coherence such that exposed surfaces are resistant to erosion, they can be the substrate for small columnar microbialites (Fig. 8B) and intraclasts can withstand movement by waves and currents (Fig. 8C).

3.6 Semi-Consolidated Mud Substrate

Two other types of renewable firm-ground substrates are noteworthy since they are likely common substrates for fossil microbialites. One occurs in submarine fine-grained sediments and develops automatically below the sediment-water interface. In most lime muds like those of Florida Bay and the Bahamas, the uppermost 15 cm grades from fluid mud to sediment with a yogurt like consistency to coherent sediment that although soft that fractures (Ginsburg and Lowenstam 1958). Strong wave action and significant bed load transport of shell fragments can scour the uppermost incoherent layer exposing the firm sediment as a potential substrate. The intraclasts of semi-coherent mud in Florida Bay and in northern Belize lagoons (RNG, personal observations) are evidence of this process.

3.7 Substrates in Peritidal Deposits

The contemporary peritidal deposits of Andros Island, which are intermittently exposed above sea level, contain both lithified substrates and firmgrounds (Figs. 10–11). Locally exposed sediments become cohesive through a combination of desiccation and microbial stabilization. One example of these peritidal firmgrounds forms on the natural levees of tidal channels (Fig. 10A and B (Hardie 1977). These levees receive fine-sand and silt sized peloids during flooding of spring tides or storms. In between these depositional events, the levees are exposed for 98 % of the year (Ginsburg et al. 1977) and develop desiccation cracks a few centimeters across and deep. At the same time cyanobacteria colonize the moist surfaces and develop a sediment-rich biofilm, coherent enough to be peeled away and to produce thin chip-like intraclasts (Fig. 10B) (Shinn et al. 1969).

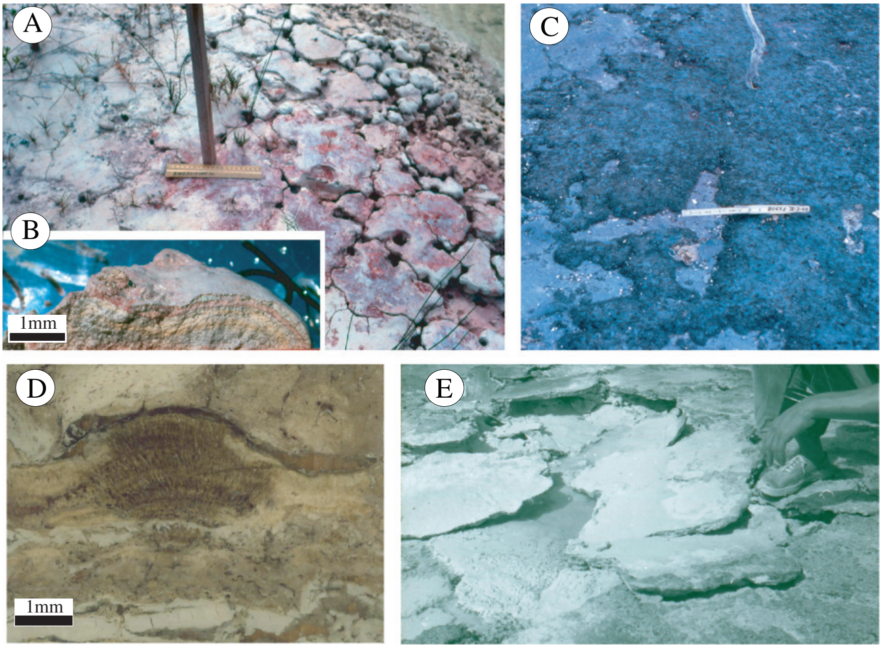

Fig. 10 Peritidal renewable substrates, northwest Andros Island, Bahamas. (**A**) View of the margin of a tidal channel showing firmgrounds of polygons produced by desiccation (See Hardie 1977). (**B**) Cross-section of a polygon in (**A**) showing the sediment-rich biofilm at the surface that contributes to the coherence of this fine-grained sediment. (**C**) A sediment rich microbial-mat with some cementation, likely induced by evaporation. These microbial mats are locally abundant on the surfaces of the Andros Island peritidal flats. (**D**) Stromatolitic structures on renewable peritidal crust from the fresh water marsh zone at Deep Creek. The light gray areas are formerly exposed and now cohesive surfaces. The darker gray and irregular areas consist of alternating laminations of the cyanobacteria *Scytonema spp.* and fine-grained carbonate sediment. Each of the radial filaments of *Scytonema* are coated by magnesium calcite (see Hardie 1977 for further details). (**E**) Large pieces of the well-cemented crust from one of several mostly exposed areas of the marine Three Creeks tidal flats of northwest Andros Island, Bahamas (described by Shinn et al., 1969 and Hardie 1977)

Thin well-cemented crusts develop on the surfaces of subaerially exposed sediments and are another lithified substrate on the peritidal deposits of Andros Island (Fig. 10E). There are similar crusts in the freshwater marshes of the Andros flats. These crusts are often covered by mushroom-like stromatolitic growths a few centimeters high that have radial and concentric internal structures composed largely of calcified filaments of the cyanobacteria *Sytonema* spp. (Fig. 10D). Each of the radial filaments of this alga are incased in carbonate Mg calcite (12–13 mol % Mg (Hardie 1977).

Intraclasts of the cemented crusts, especially those that occur as edgewise conglomerates (Fig. 11A) can also be substrates for stromatolites. The Upper Cambrian carbonates of Western Maryland are a well-documented example of stromatolites

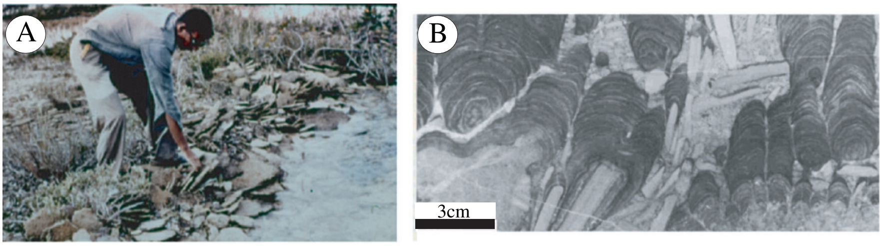

Fig. 11 (**A**) Edgewise conglomerate of platy intraclasts of the cemented crust. Breaking waves on a shoreline of Andros Island accumulated these book-like clusters. (**B**) Stromatolites growing on an edgewise conglomerate from peritdal sequences in Upper Cambrian of Maryland, offering an example of stroamtolite development upon substrates likely developed in a peritidal environment (photo Robert Demicco)

preferentially developing on clasts of cemented crusts (Demicco 1985). Due to the prevalence of firmgrounds and hardgrounds, when the surfaces of tidal flat deposits are flooded by a relative rise of sea level, there will be abundant substrates for a new generation of stromatolites.

4 Sediment Supply for Holocene Stromatolites

The prevalence of calcareous sands is a key element in the development of Holocene microbialites. The predominant grain types on Great Bahama Bank are peloids, well rounded ovoid or circular sand sized grains, and superficial ooids (Illing 1954), which are peloids thinly coated with concentric layers of aragonite in areas of persistent sand movement. The majority of peloids are likely fecal pellets of deposit-feeding invertebrate. Some peloids are also ooids, that have lost their concentric layering due to penecontemporaneous recrystallization or cyanobacteria microboring (Reid and MacIntyre 1998, 2000). The varying stages of this transformation can be observed in most thin sections of ooid sand.

The twice-daily tidal currents provide the peloid and ooid sand that is the building material for both the stromatolites and unlaminated microbiolites in Adderly Channel and elsewhere in the Exumas Island Chain. Ebb tidal currents, channeled by topography, transport peloids from the bankward side of Adderly Channel area to nourish the sand bar. In addition, some peloids are formed within the bar complex. Flood tidal currents produce bankward-migrating sand waves that deliver the sand to developing microbialites. The near continuous sand movement correlates with the formation of the oolitic coatings (Dill et al. 1986). It also limits colonization of microbialites by boring or encrusting metazoans and algae. A major decrease or cessation in the sediment flux results in the development of a algae-dominated benthic community (Dill et al. 1986). When stromatolites covered by an algal beard are sectioned they commonly reveal a horizon of bivalve and sponge borings along the margins (authors observations), suggesting that the eukaryotic community does not result in accretion. Only when there are regular high levels of sediment supply can uninterrupted growth of microbialites be maintained.

5 Discussion

5.1 Substrate Limitations

The consistent association of columnar Bahamian microbialites and with hard and firm surfaces in subtidal settings is convincing evidence that coherent substrates are necessary for the development of these microbial structures. At Adderly Channel, and in subtidal settings more generally, there may be substrate limitations due to high levels of bedload sediment and this sediment's frequent movement. Cyanobacteria readily colonize on most surfaces, including on uncemented sand and silt; however, the resulting stabilized surfaces do not appear to provide a suitable foundation for large columnar stromatolites. It is possible that such stabilized sediment surfaces could become submarine hardgrounds, but confirmation of this transformation will require much detailed sampling and high resolution dating.

Peritidal successions have more potential substrates than subtidal successions. However, colonization and accretion of sizeable stromatolites on those substrates requires a relative rise of sea level. The record of a transgression of peritidal deposits should show an upward progression from planar laminated substrates, to low relief arches succeeded by, distinct columnar stromatolites. A well-described fossil example of this succession is found in the cycles of stromatolites forming on peritidal laminates and conglomerates in the Proterozoic Atar Group in Mauritania (Bertrand Sarfati 1972)

In the Precambrian when there were no grazing or burrowing metazoans, benthic microbial communities would likely have been nearly ubiquitous on all surfaces. Even in the Cambrian, there is evidence for extensive benthic microbial mats (for example, Bailey et al. 2006). Given these circumstances, it is at first surprising that stromatolites in these strata often have a restricted distribution or are isolated to distinct horizons (for example, Bertrand Sarfati 1972; Demicco 1985). Although the anatomy of a carbonate platform is obviously complex and controlled by numerous factors, our examination of the Bahamian stromatolites prompts a simple explanation for the sporadic distribution of the stromatolites. In many platforms there is likely to be local substrate restriction in areas with a substantial mobile silt/sand sized detrital load, since our study of the Bahamian microbialites suggests that the formation of sizable stromatolites is dependent a firm foundation. Therefore, high amounts of detrital sediment may lead to a more heterogeneous distribution of bioherms and reefs. In areas where stromatolites are nearly ubiquitous—for example, the Paleoproterozoic Great Slave Lake carbonates (Hoffman 1974; Pope and Grotzinger 2003; Sami and James 1993) or Archean Steep Rock Group carbonates (Wilks and Nisbet 1985, 1988)—there is a small detrital load and abundant syndepositional cementation to provide widespread firm foundations.

5.2 Renewable Substrates and Stromatolite Initiation

The availability of renewable substrates allows for the repeated initiation of columnar stromatolites. In systems with low accommodation space (e.g. peritidal deposits) all of the stromatolites will be isolated to distinct horizons because the accommodation space is almost instantaneously filled. In contrast, in subtidal settings, such as the Bahamian tidal channels, stromatolites can develop varying levels of synoptic relief. If continuously forming substrates are available, there is likely to be evidence for different ages of stromatolite initiation. This process is clearly visible in Addelry Channel in the Bahamas and in subtidal zone in the famous Western Australia Shark Bay modern stromatolite locality. In contrast, there is limited variation in synoptic relief in the peritidal and tidal stromatolites at Shark Bay (Fig. 2) or in the Bahamas. Variability in initiation patterns within a stromatolite horizon should be preserved in the rock record. Therefore, examination of the initiation patterns of ancient microbialites may offer a means to discern between subtidal and tidal/peritidal microbialite systems when diagnostic sedimentary features are lacking.

5.3 Early Diagenesis affects Later Growth

The Bahamian stromatolites fields are influenced by the interplay of diagenetic process and latter growth. The submarine hard-grounds and firm-grounds are extreme examples of how early diagenesis can transform unconsolidated sediment to hard and firm substrates. The early diagenetic recrystallization in the hard-grounds and in the surfaces of the firm-grounds appears to be largely driven by multiple stages of dissolution and reprecipitation, but cyanobacteria microboring is also undoubtedly also a contributor. Dissolution requires temporary undersaturation, which is related to the degradation of organics because Adderly Channel seawater is highly supersaturated with respect to calcite and aragonite. Analysis of sediment pore waters indicates there is widespread carbonate dissolution and reprecipitation on shelf sediments (Burdige and Hu 2005; Hu and Burdige 2007; Walter et al. 1993); this study and more extensive study of other localities (Macintyre et al. 2000; Reid et al. 1995; Reid et al. 1992; Reid et al. 2000) provides confirming petrographic evidence. Carbonate alteration in modern sediments has been linked with benthic sulfur cycling and aerobic respiration (Hu and Burdige 2007; Ku et al. 1999).

Uncertainty persists about the precise mechanism responsible for the widespread precipitation of carbonate as cement in the sediments of Great Bahama Bank. The relatively small amount of calcium carbonate that can be precipitated from a pore volume of seawater means that countless pore volumes are required to achieve significant cementation. The selective cementation around animal borings evidences the role of increased flow in cementation. The widespread occurrence of cements, ooids, lithification of fecal pellets (peloids) and possibly whitings, clouds of fine-grained carbonate sediment, testify to the pervasive non-skeletal precipitation. All of these processes are likely to some degree influenced by microbial processes. However, without detailed analyses of porewaters, and the isotope ratios of the cements it is difficult to gauge the degree to which microenvironments of carbonate precipitation were shifted from ambient seawater.

6 Conclusions

Even though cyanobacterial mats readily colonize almost any surface in the tidal channels, tidal bars, and shorelines of much of the Bahamas, stromatolite development appears to be contingent upon a stable substrate. Subtidal and peritidal environments on Great Bahama Bank provide a spectrum of these substrates for stromatolites that may be a guide for interpreting the origins of fossil substrates.

In shallow oceanic tidal channels to depths of at least 8 m of the Exuma Islands, large (up to 2 m tall) stromatolites develop preferentially on inherited and renewable substrates. The inherited substrates are well-cemented rock surfaces—Pleistocene limestone often veneered with paleosol or caliche-like crusts. The renewable substrates include submarine hardgrounds, firmgrounds, and conglomerates of skeletal debris and intraclasts. The firmgrounds and conglomerates, which are deposited during large storms, and are an example of rare events having a large effect on latter accretion.

The well-studied humid peritidal deposits of Andros Island offer examples of potential substrates. Hardgrounds a few cm thick develop on exposed surfaces. Coherence is caused by capillary evaporation aided cementation, stabilization from the microbial mats, and hardening through desiccation. The prevalence of firmgrounds and cemented crusts in peritidal environments makes them a likely foundation for development of stromatolites during a relative rise of sea level.

The penecontemporaneous cementation and early diagenetic recrystallization that produces submarine and subaerial hardgrounds and in places enhances the durability of firm grounds is a notable example of the feedback of early diagenesis on depositional processes.

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References

Andres MS, Reid RP (2006) Growth morphologies of modem marine stromatolites: a case study from Highborne Cay, Bahamas. Sediment Geol 185:319–328

Andres MS, Sumner DY, Reid RP, Swart PK (2006) Isotopic fingerprints of microbial respiration in aragonite from Bahamian stromatolites. Geology 34:973–976

Arp G, Reimer A, Reitner J (1999) Calcification in cyanobacterial biofilms of alkaline salt lakes. Eur J Phycol 34:393–403

Arp G, Reimer A, Reitner J (2003) Microbialite formation in seawater of increased alkalinity, Satonda crater lake, Indonesia. J Sediment Res 73:105–127

Bailey JV, Corsetti FA, Bottjer DJ, Marenco KN (2006) Microbially-mediated environmental influences on metazoan colonization of matground ecosystems: evidence from the Lower Cambrian Harkless Formation. Palaios 21:215–226

Bertrand Sarfati J (1972) Paleoecologie de certains stromatolites en recifs des formations d precambrien superieur de groupe d' Atar (Mauritanie, Sahara occidental): creation d'especes nouvelles de ces recifs Palaeogeography, Palaeoclimatology, Palaeoecology 11:33–63

Black M (1933) The algal sediments of Andros Islands, Bahamas. R Soc Lond Philos Trans, B 222:165–192

Browne KM, Golubic S, Seong-Joo L (2000) Shallow marine microbial carbonate deposits, In: Riding R, Awramik SM (eds) Microbial sediments. Springer-Verlag Publishing, Berlin, pp 233–249

Burdige DJ, Hu XP (2005) Isotopic evidence for shallow-water carbonate dissolution and reprecipitation. Geochimica et Cosmochimica Acta 69:A130–A130

Demicco RV (1985) Platform and off-platform carbonates of the Upper Cambrian of western Maryland, USA. Sedimentology 32:1–22

Dill RF (1991) Subtidal Stromatolites, Ooids, and Crusted-Lime Muds at the Great Bahama Bank Margin. In: Osborne RH (ed) From Shoreline to Abyss, SEPM Special Publication: Tulsa, Society for Sedimentary Geology pp 147–171

Dill RF, Shinn EA, Jones AT, Kelly K, Steinen RP (1986) Giant Subtidal Stromatolites Forming in Normal Salinity Waters. Nature 324:55–58

Dravis JJ (1983) Hardened subtidal stromatolites, Bahamas. Science 219:385–386

Feldman M, McKenzie J (1998) Stromatolite-thrombolite associations in a modern environment, Lee Stocking Island, Bahamas. Palaios 13:201–212

Ginsburg RN, Hardie LA, Bricker OP, Garrett P, Wanless H (1977) Exposure index: a quantitative approach to defining position within the Tidal Zone. In: Hardie LA (ed) Sedimentation on the modern carbonate tidal flats of northwest Andros Island, bahamas, The John Hopkins University Press, Baltimore pp 7–12

Ginsburg RN, Lowenstam HA (1958) The Influence of Marine Bottom Communities on the Depositional Environment of Sediments. J Geol 66:310–318

Gischler E, Lomando AJ (1997) Holocene cemented beach deposits in Belize. Sediment Geol 110:277–297

Hardie LAE (1977) Sedimentation on the Modern Carbonate Tidal Flats of Northwest Andros Island, Bahamas. Studies in Geology 22, The John Hopkins University Press, Baltimore

Hoffman P (1974) Shallow and Deep-Water Stromatolites in Lower Proterozoic Platform-to-Basin Facies Change, Great-Slave-Lake, Canada. AAPG Bull 58:856–867

Hu XP, Burdige DJ (2007) Enriched stable carbon isotopes in the pore waters of carbonate sediments dominated by seagrasses: Evidence for coupled carbonate dissolution and reprecipitation. Geochimica et Cosmochimica Acta 71:129–144

Illing LV (1954) Bahamian Calcareous Sands. Am Assoc Pet Geol Bull 38:1–95

Ku TCW, Walter LM, Coleman ML, Blake RE, Martini AM (1999) Coupling between sulfur recycling and syndepositional carbonate dissolution: evidence from oxygen and sulfur isotope composition of pore water sulfate, South Florida Platform, USA. Geochimica et Cosmochimica Acta 63:2529–2546

Logan BW, (1961) Cryptozoon and Associate Stromatolites from the Recent, Shark Bay, Western-Australia: J Geol 69:517–529

Macintyre IG, Prufert-Bebout L, Reid RP (2000) The role of endolithic cyanobacteria in the formation of lithified laminae in Bahamian stromatolites. Sedimentology 47:915–921

Macintyre IG, Reid RP, Steneck RS (1996) Growth history of stromatolites in a Holocene fringing reef, Stocking Island, Bahamas. J Sediment Res 66:231–242

Monty CVL (1976) The Origin and Development of Cryptalgal Fabrics, In: Walter MR (ed) Stromatolites. Developments in Sedimentology Amsterdam Elsevier, pp 193–251

Palmer M (1979) Holocene Facies Geometry of the Leeward Bank Margin, Tongue of the Ocean, Bahamas, Unpublished Master's thesis, University of Miami, Miami pp 198

Papineau D, Walker JJ, Mojzsis SJ, Pace NR (2005) Composition and structure of microbial communities from stromatolites of Hamelin Pool in Shark Bay, Western Australia. Appl Environ Microbiol 71:4822–4832

Pierson BJ, Shinn EA (1983) Distribution and Preservation of Carbonate Cements in Pleistocene Limestones of Hogsty Reef Atoll, Southeast Bahamas. AAPG Bull 67:534–534

Playford PE, Cockbain AE (1976) Modern Algal Stromatolites at Hamelin Poor, a Hypersaline Barred Basin in Shark Bay, Western Australia, In: Walter MR (ed) Stromatolites: developments in sedimentology 20. Amsterdam, Elsevier, pp 389–413

Pope MC, Grotzinger JP (2003) Paleoproterozoic Stark Formation, Athapuscow Basin, Northwest Canada: Record of cratonic-scale salinity crisis. J Sediment Res 73:280–295

Reid RP, MacIntyre IG (1998) Carbonate recrystallization in shallow marine environments: a widespread diagenetic process forming micritized grains. J Sediment Res 68:928–946

Reid RP, MacIntyre IG (2000) Microboring versus recrystallization: further insight into the micritization process. J Sediment Res 70:24–28

Reid RP, Macintyre IG, Browne KM, Steneck RS, Miller T (1995) Modern Marine Stromatolites in the Exuma-Cays, Bahamas – Uncommonly Common. Facies 33:1–17

Reid RP, Macintyre IG, Post JE (1992) Micritized Skeletal Grains in Northern Belize Lagoon – a Major Source of Mg-Calcite Mud. J Sediment Petrol 62:145–156

Reid RP, Macintyre IG, Steneck RS (1999) A microbialite/algal ridge fringing reef complex, Highborne Cay, Bahamas. Atoll Res Bull 466:1–18

Reid RP, Visscher PT, Decho AW, Stolz JF, Bebout BM, Dupraz C, Macintyre IG, Paerl HW, Pinckney JL, Prufert-Bebout L, Steppe TF, DesMarais DJ (2000) The role of microbes in accretion, lamination, and early lithification of modern marine stromatolites. Nature 406:989–992

Sami TT, James NP (1993) Evolution of an Early Proterozoic Foreland Basin Carbonate Platform, Lower Pethei Group, Great Slave Lake, North-West Canada. Sedimentology 40:403–430

Semikhatov M, Gebelein MC, Cloud P Awramik S, Benmore W (1979) Stromatolite morphogenesis—progress and problems. Can J Earth Sci 19:922–1015

Shapiro RS, Aalto KR, Dill RF, Kenny R (1995) Stratigraphic Setting of a Subtidal Stromatolite Field, Iguana Cay, Exumas, Bahamas, In: Curran HA, White B (eds) Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda, 300, Geological Society of America, Boulder pp 139–156

Shinn EA, Lloyd RM, Ginsburg RN (1969) Anatomy of a Modern Carbonate Tidal-flat, Andros Island, Bahamas. J Sediment Petrol 37:1202–1228

Shinn EA, Steinen RP, Dill RF, Major RP (1993) Lime-mud layers in high-energy tidal channels; a record of hurricane deposition. Geology 21:603–606

Taft WH, Arrington F, Haimovitz A, MacDonald M, Woolheater C (1968) Lithification of Modern Carbonate Sediments at Yellow Bank, Bahamas. Bull Mar Sci 18:762–828

Visscher PT, Reid RP, Bebout BM (2000) Microscale observations of sulfate reduction: correlation of microbial activity with lithified micritic laminae in modern marine stromatolites. Geology 28:919–922

Visscher PT, Reid RP, Bebout BM, Hoeft SE, Macintyre IG, Thompson JA (1998) Formation of lithified micritic laminae in modern marine stromatolites (Bahamas): the role of sulfur cycling. Am Mineral 83:1482–1493

Walter LM, Bischof SA, Patterson WP, Lyons TW (1993) Dissolution and Recrystallization in Modern Shelf Carbonates – Evidence from Pore-Water and Solid-Phase Chemistry. Philos Trans R Soc Lond A 344:27–36

Waterbury JB, Watson SW, Guillard RRL, Brand LE (1979) Widespread Occurrence of a Unicellular, Marine, Planktonic, Cyanobacterium. Nature 277:293–294

Wilks ME, Nisbet EG (1985) Archean Stromatolites from the Steep Rock Group, Northwestern Ontario, Canada. Can J Earth Sci 22:792–799

Wilks ME, Nisbet EG (1988) Stratigraphy of the Steep Rock Group, Northwest Ontario – a Major Archean Unconformity and Archean Stromatolites. Can J Earth Sci 25:370–391