

Modern stromatolite reefs fringing a brackish coastline, Chetumal Bay, Belize

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ABSTRACT

Reef-forming stromatolites have been discovered along the windward shoreline of Chetumal Bay, Belize, just south of the mouth of the Rio Hondo. The reefs and surrounding sediment are formed by the precipitation of **submicrocrystalline** calcite upon the sheaths of filamentous cyanobacteria, principally *Scytonema*, under a seasonally fluctuating, generally **brackish** salinity regime (0‰–10‰). Well-cemented, wave-resistant buttresses of coalesced stromatolite heads form arcuate or club-shaped reefs up to 42 m long and 1.5 m in relief that are partially emergent during low tide. Oncolitic rubble fields are present between well-developed reefs along the 1.5 km trend, which parallels the mangrove coastline 40–100 m offshore. The mode of reef growth, as illustrated by surface relief and internal structure, changes with increasing water depth and energy, proximity to bottom sediments, and dominant cyanobacterial taxa. Sediment trapping and binding by cyanobacteria are of limited importance to reef growth, and occur only where stromatolite heads or oncolites are in direct contact with the sandy sea floor. Radiocarbon-dated mangrove peat at the base of the reef suggests that it began to form about 2300 yr B.P., as shoreline encrustations that were stranded offshore following storm-induced retreat of the mangrove coast.

INTRODUCTION

Although strict definitions vary, **stromatolites** can generally be described as laminated organosedimentary structures produced by the sediment trapping, binding, and/or precipitation activities of photosynthetic microbial communities, principally cyanobacteria (Kalkowsky, 1908; Awramik, 1984; Ginsburg, 1991). Riding (1977) subclassified stromatolites formed primarily by the calcification (encrustation) of cyanobacteria as "skeletal" stromatolites, a term that we employ here.

Fossilized stromatolites from the Archean of Western Australia and South Africa represent the oldest evidence (–3500 Ma) of life on Earth (Schopf, 1983). Stromatolites later expanded in abundance and diversity during the Mesoproterozoic, forming true reefs that were among the largest in Earth history (Awramik, 1984; Grotzinger, 1989). However, during the Neoproterozoic, and again in the early Paleozoic, marine stromatolites declined markedly. This decline has been attributed to various factors, including the appearance of marine meiofaunal and macrofaunal grazers and burrowers (Garrett, 1970; Walter and Hays, 1985), competition with macrophytes (Monty, 1973; Fanner, 1989), and the onset of coarse, skeletal sedimentation (Pratt, 1982). The post-Cretaceous restriction of skeletal stromatolites to only lacustrine settings has led some workers to suggest significant changes in seawater chemistry (Riding, 1982; Pentecost and Riding, 1986).

Unlike many of their Precambrian through Cretaceous predecessors, modern-day, calcite-precipitating stromatolites are most likely found in low-energy, hypersaline bays and ponds (Logan, 1961; Dakoski and Bain, 1984; Mann and Nelson, 1989; Neumann et al., 1989), or freshwater lakes (Cohen and Thouin, 1987; Osborn et al., 1982; Casanova, 1986; Thompson et al., 1990). Though modern Bahamian stromatolites discovered by Dravis (1983), Dill et al. (1986), and Reid and Browne (1991) are located in unrestricted, high-energy marine settings, they form mostly through sediment trapping and binding, and there is only minor cementation between allochthonous grains. Modern stromatolites that formed through cyanobacterial calcification in open-marine, reefal settings remain unreported, resulting in a paucity of analogues appropriate to the interpretation of fossil counterparts having a "skeletal" framework.

Herein we report modern-day cyanobacterial communities in a turbulent, schizohaline, coastal setting which are forming massive, laterally and vertically zoned stromatolite reefs through the direct precipitation of calcite. Their intertidal to shallow subtidal depth, coastal windward location, and control on local sedimentation provide a new modern analogue for fossil predecessors.

ENVIRONMENTAL SETTING

Shallow-water carbonate depositional environments of the Belize shelf were de-

scribed by Pusey (1975). Our study was located in Chetumal Bay, along the northernmost coast of Belize, immediately south of the mouth of the Rio Hondo (Fig. 1). Stromatolite reefs are located parallel to the mangrove coast in <1.5 m of water, between 40 and 100 m offshore. Location along the northeast coast places the reefs in a turbulent, high-energy environment dominated by the prevailing northeast trade winds (typically 12–20 knots). Stoddart (1963) reported that during 1931–1961, hurricanes hit this area every six years, on average. Ongoing, storm-induced retreat of the shoreline is evident in recently killed coastal mangroves with mangled prop roots and in relict coastal headlands now stranded just offshore as isolated mangrove islands. Turbidity is high, and cloudy, milky-white waters generally afford <10 cm visibility. The climate is tropical, and water temperatures range from 25 to 30 °C. Annual rainfall is ~124 cm, and the area is characterized by a short dry season (February–April) and a long wet season (May–January). The Rio Hondo drains a karstic terrain of Tertiary through Pleistocene carbonates, creating brackish waters in Chetumal Bay which are Ca rich (800 ppm) and saturated to supersaturated with calcite (Pusey, 1975). Strong seasonality in rainfall and proximity to river outflow create a generally brackish, fluctuating salinity (schizohaline) regime in the study area. Our dry-season measurements (April 1991) among the stromatolites indicate brackish salinities ranging from 4‰ to 8‰; those of the wet season (July–August 1961) reported by Pusey (1975) indicate that salinity is always <10‰, and that the water can become essentially fresh. The maximum lunar tidal range is about 0.5 m, although winter storms ("northers") frequently create an enhanced tidal range of 0.8 m (Pusey, 1975). Inhabitants of Corozal observe that winds can shift the strandline up to 20–30 m offshore during storms. Metzger (1925) noted particularly dramatic storm effects during a 1920 hurricane, during which coastal waters receded several miles from the battered mangrove coast.

STROMATOLITE REEFS

Massive, well-developed stromatolite reefs alternate with oncolite rubble fields.

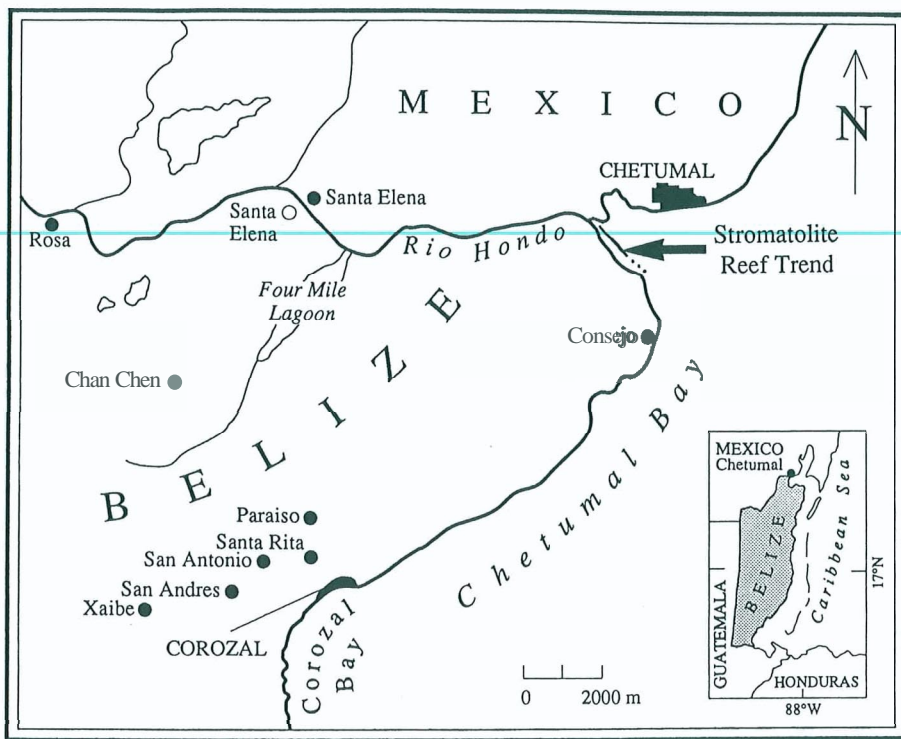


Figure 1. Location map of stromatolites discovered in Belize, Central America. Primary study area is coastal reef complex in schizohaline setting immediately south of mouth of Rio Hondo in Chetumal Bay.

along the discontinuous, 1.5-km-long reef trend in Chetumal Bay. Individual stromatolitic heads have grown upward and coalesced, forming well-cemented, wave-resistant buttresses 1–4 m in length and width and with multiple basal "roots." Groups of subtidal to intertidal buttresses form arcuate or club-shaped reefs up to 42 m long and 1.5 m in relief. Many reef crests emerge 10–15 cm above water during low tide (Figs. 2 and 3).

A consistent lateral zonation was observed across the reef (Fig. 2). Zones include a fore reef of submerged heads and talus in rippled sand, an intertidal reef crest of asym-

metrical buttresses sloping $<10^\circ$ shoreward (Fig. 3), and a subtidal back-reef flat of individual heads and oncolites in sand and gravel. Many closely packed oncolites in the reef flat have grown laterally, coalescing into immobile, compound oncolite slabs. Sediment in all zones is dominated by unconsolidated, well-sorted to moderately well sorted medium sand. Molds of relict mangrove prop roots are common at the base of the reef crest, which is typically underlain by a thin horizon of stromatolitic sand and gravel above calcitic mud and mangrove peat. Cyanobacterial mats were not found on the

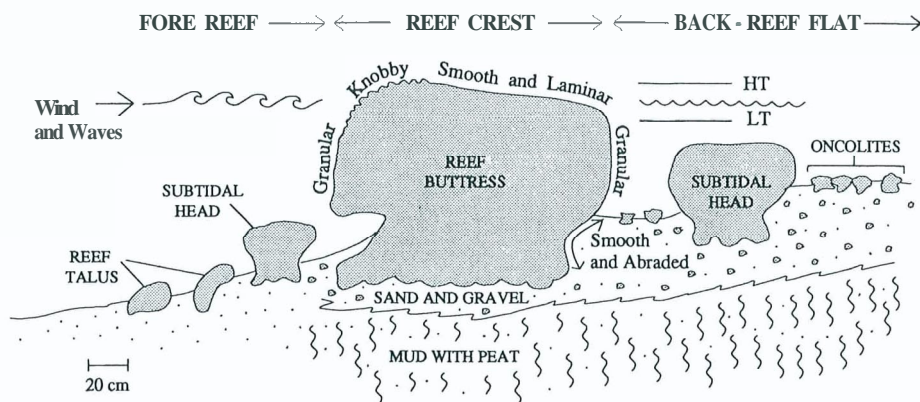


Figure 2. Schematic cross section of prograding, windward reef buttress illustrating lateral reef zones and vertical changes in surface relief. Note mangrove peat base. Coalescence of individual oncolites in back-reef flat provides alternative foundation for future stromatolite growth. HT is high tide; LT is low tide.

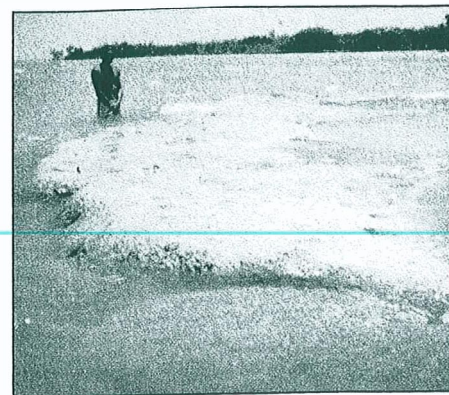


Figure 3. Massive windward reef crest offshore of mangrove coastline. Reef crest dips gently shoreward. Fleshy, smooth, and laminar mat of *Schizothrix* on uppermost surface is exposed at low tide. Windward, lower intertidal part of buttress, on left, shows knobby surface relief composed of prominent *Scytonema* "buttons."

sandy sea floor surrounding the reefs, nor were hardgrounds created by inorganic, interparticle cementation.

In stark contrast to the diverse, coral-dominated buildups of the outer barrier reef system, the stromatolite reefs nearshore maintain only a few secondary, nonstructural biota tolerant of schizohaline conditions. The most common of these are the green alga *Batophora oerstedii* and assorted pennate diatoms; both are ubiquitous on upper reef surfaces. The bivalve *Mytilopsis sallei*, a relative of the zebra mussel, is commonly attached to and entombed within the stromatolites. *Serpulid* worm tubes are common in cryptic crevices, such as reef-crest overhangs and the undersides of oncolites. The salt-tolerant plant *Sporobolus virginicus*, a tropical and warm-temperate grass more commonly found above the high-tide mark, occurs in patches on some emergent crests. Living macrograzers were not observed during the brackish conditions of our April (dry season) visit, although some ostracode and microgastropod fragments were seen in reefal sediments.

RESULTS AND DISCUSSION

The wave-resistant, laterally and vertically zoned stromatolite reef complex found along the windward coast of Belize is restricted to a 1.5-km-long stretch adjacent to the Rio Hondo outflow. Salinity in this area alternates seasonally from fresh to brackish. Although other factors may play a role, proximity to the Rio Hondo certainly fosters cyanobacterial mat and stromatolite reef development through the exclusion of common macrograzers, many of which are intolerant of schizohaline salinity regimes (Garrett, 1970). In addition, calcite oversaturation created by the mixing of seawater with freshwater runoff should encourage calcite

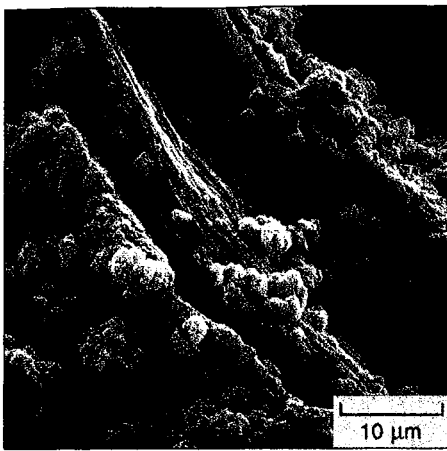


Figure 4. Scanning electron micrograph of desiccated sheath of cyanobacterium *Scytonema*, showing anhedral calcite encrustation.

precipitation in coastal Chetumal Bay. Although conditions that typically foster inorganic hardground formation were present (i.e., calcite oversaturation; winnowed, sandy sea floor; high-energy setting), no inorganic hardgrounds were found here. Cementation is confined to areas within the reef framework, and particularly those sites in close proximity to *Scytonema* filaments, the primary structural element (Fig. 4). Calcification appears to be a microbially induced phenomenon, perhaps a consequence of pH elevation during photosynthesis and CO_2 withdrawal by filamentous cyanobacteria (Merz, 1992).

The stromatolites are composed primarily of submicrocrystalline (1–2 μm) anhedral calcite (<2 mol% MgCO_3 ; determined using methods of Goldsmith and Graf, 1958) precipitated upon the sheaths of filamentous cyanobacteria, principally *Scytonema* (Fig. 4). Surface relief and dominant cyanobacterial taxa change with water depth and energy, and with proximity to the mobile, sandy sediment floor (Fig. 2). Very slightly calcified, smooth laminar mats of *Schizothrix* and *Phormidium* dominate the uppermost, emergent surfaces of the reef. This fleshy, poorly indurated surface gives way to a well-cemented, knobby zone of *Scytonema* and *Phormidium* "buttons" (0.5–2-cm-diameter growths) within the lower intertidal zone (Figs. 2 and 3). Irregular, knobby relief is most conspicuously developed on the higher energy, windward sides of each buttress (Fig. 3). Smaller surface irregularities (growths <0.5 cm in diameter) created by *Scytonema* and *Phormidium* in the deeper subtidal zone (>20 cm depth) forms a subdued, "granular" surface relief. A lowermost smooth and abraded surface exists at the stromatolite-sediment interface. The smooth and abraded zone is composed predominantly of calcified *Scytonema* and *Phormidium* filaments; however, here they

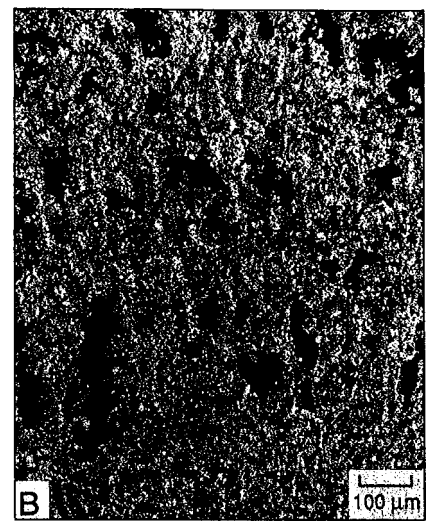


Figure 5. A: Typical internal columnar structure formed by stacked, fanlike arrays of calcified *Scytonema* filaments. Conspicuous large-scale bands are created by white microlaminae of dense micritic cement. Several small-scale bands (detail in B) are visible along left-center margin. Grains have percolated down into spaces between digitate columns and are not bound by filaments. B: Closeup of small-scale bands illustrates erect, radiating filaments, and prostrate, collapsed filaments. Repetitive, perhaps seasonal pattern of alternating filament orientation may be related to changes in ambient salinity.

are commonly blunted and convoluted, and they alternate with closely spaced micritic cement layers. This lowermost zone is the only site where true interfilament trapping and binding of loose sediment was observed. Thin sections of trapped sediment and surrounding reefal sediment reveal remnant cyanobacterial filaments, indicating a stromatolitic origin for >95% of all reef-associated grains.

With the exception of the uppermost smooth and laminar zone, which is dominated by slightly encrusted *Schizothrix*, internal structure is typically columnar and dominated by *Scytonema* (Fig. 5A). Within each column a consistent repetitive microfabric is noted: well-calcified, fanlike arrays of 20–30- μm -diameter *Scytonema* filaments (Fig. 5B). Vertical stacking of these radiating fans produces the digitate pattern of growth columns, generally ≤ 1 cm in width, which terminate at the stromatolite surface as subdued granular relief or enlarged (0.5–2 cm diameter) buttons (Figs. 3 and 5A). The spaces between columns typically contain sand cemented by a minute amount of point-contact submicrocrystalline calcite.

Peat beneath two sites was radiocarbon dated by Beta Analytic; ages are reported as uncorrected radiocarbon years before present (A.D. 1950). A sample just behind the reef crest and overlain by an oncolite slab yielded a date of 2340 ± 80 yr B.P. Another sample located at the reef crest directly beneath a 60 cm section of stromatolite growth produced a similar date, 2240 ± 190 yr B.P. This date suggests an average accretion rate of 27 cm/ka for the overlying stromatolite head. This simple growth-rate calculation

neglects the lateral accretion (seaward progradation) inferred from the asymmetrical profile of the reef crest (Fig. 2); therefore, it is considered a conservative, as well as time-averaged, estimate. Several nearby buttresses have grown up to about 1.5 m above the sea floor. If we assume that these build-ups began contemporaneously, a faster accretion rate of 65 cm/ka is possible.

Two types of banding within the digitate growth columns are apparent in cross section: large-scale bands (~2 mm wide) of dense micritic cement forming distinctive, white microlaminae (Fig. 5A) and, between the larger bands, six to eight small-scale bands (~0.3 mm wide) created by paired horizons of erect and prostrate *Scytonema* filaments (Fig. 5B). Close inspection of these smaller bands indicates no change in the structural element *Scytonema*, but simply a change in its orientation, between filaments in life position and filaments lying prostrate.

On the basis of our limited radiocarbon data and resultant growth rate calculations, the larger bands appear to form about every seven to eight years. Stoddart (1963) noted that major storms occurred with comparable frequency between 1931 and 1962, on average every six years. Such storms create periods of widespread exposure and desiccation; in the calcite-saturated setting of the stromatolitic heads, these periods should foster inorganic cementation of outer surfaces and may account for the large-scale, inorganic bands. Growth-rate data suggest that the six to eight intervening smaller scale bands may correspond roughly to an annual growth period. Furthermore, prostrate filaments suggest a conspicuous, perhaps an-

nual period of interrupted growth **contrast-**ing with erect filaments in preserved life orientation (Fig. 5B). Seasonal changes in local salinity may thus account for the observed disruptions of filament growth which create these small-scale organic bands.

Interpreting the mode of accretion for ancient fossilized stromatolites is **problematic** and typically involves choosing between grain trapping and binding, on the one hand, and in situ precipitation mechanisms (Fairchild, 1991), on the other. In the Belizean stromatolite reefs, the accretion mechanism changes during the growth history of the individual head. The smooth and abraded surfaces of heads in direct contact with the sediment floor show **true** grain trapping and binding between filaments, and therefore this mechanism accounts for some net accretion early in their growth history. However, upon sufficient growth upward and away from the sea-floor source of sediment, calcite precipitation dominates accretion, and the stromatolites become truly skeletal (see Riding, 1977). These observations demonstrate that the alternative growth mechanisms described in the formation of fossil stromatolites are not mutually exclusive, and can simply reflect sediment availability and synoptic relief.

The origin and growth history of the stromatolite reef complex is suggested by several observations. Calcified mats encrusting mangrove prop roots along the modern eroding coastline, molds of relict mangrove roots at the base of the stromatolite heads, and the position and age of the peat underlying the reef complex all suggest that it began as a mangrove shoreline encrustation at least 2300 yr B.P. These encrustations were left stranded offshore following episodic, **storm-**induced retreat of the mangrove coast, and thereby provided the foundation for the further growth of a modern fringing reef. Partial emergence and the prograding, asymmetrical form of the present-day reef crest further indicate that such growth has not only kept pace with the rise of Holocene seas, but has begun to exceed it.

SUMMARY AND CONCLUSIONS

Wave-resistant, laterally and vertically zoned stromatolite reefs are forming along the modern **schizohaline** coastline of northernmost Belize. The massive buildups are truly skeletal stromatolites, in that they are formed almost entirely by calcite precipitation around the sheaths of the filamentous cyanobacterium *Scytonema*. Vertical patterns in surface relief are directly related to water depth and energy, proximity to the sediment floor, and dominant cyanobacterial **taxa**. The stromatolite reef is the primary source of surrounding carbonate sediment.

Grain trapping and binding are of limited significance to overall reef growth, and are observed **only** at basal sites in **direct** contact with the mobile, sandy sea floor. The stromatolite reef complex has evolved from mangrove shoreline encrustations that were stranded offshore during **storm-induced** coastline retreat, beginning at ~2300 yr B.P. Ongoing processes of stromatolite reef growth and sedimentation observed in Belize may improve our understanding of ancient stromatolite reefs in similar **high-en-**ergy coastal settings.

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