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Further remarks on the role of pro-thrombolites in the origin of coastal lagoons for Northwestern Mexico

Nuevas observaciones sobre el papel de protrombolitos en el origen de lagunas costeras del NW de México

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ABSTRACT

Along the margins of coastal lagoons in Baja California Sur, Mexico, cyanobacteria-dominated communities form thick mats that eventually generate consolidated mud platforms or pro-thrombolites (unlithified thrombolites). Pro-thrombolite platforms grow seaward and form spits that alter water flow and promote sand deposition that develop into barriers, thus influencing coastal geomorphology, promoting lagoon formation. In this paper we provide evidences on the role of pro-thrombolites in the generation of coastal lagoons that includes different regions of NW Mexico where pro-thrombolite and/or thrombolithic platforms are common. In Bahía Magdalena, desiccating microbial mats are dominated by *Microcoleus chthonoplastes* Thuret ex Gomont and their remaining empty sheats occur together with lithified structures (thrombolites) cemented with micrite, considered of biotic origin. Previously proposed as a lacunar process, it is now suggested that pro-thrombolithic development leading to coastal lagoon formation actually occurs in non-lacunar environments with similar hidrological conditions. Likewise, this process is further enhanced once the coastal lagoon has been formed. We also suggest that the establishment of mangrove forests is indeed preceded by the formation of prothrombolithic platforms that provide a stabilized substrate for these plants in tropical and subtropical coastal lagoons.

Key words: Coastal lagoons, Cyanophyte mats, geomorphology, pro-thrombolites.

RESUMEN

A lo largo de los márgenes de lagunas costeras de Baja California Sur, México, comunidades dominantes de cianofitas forman tapetes conglomerados, gruesos que eventualmente generan plataformas lodosas consolidadas o protrombolitos, que permanecen sin litificar. Las plataformas protrombolíticas crecen mar adentro formando puntas que alteran el flujo de las corrientes y por consiguiente el transporte y acumulación de sedimentos, creando barreras e influyendo en la geomorfología costera, lo que resulta en la formación de lagunas costeras. En este trabajo se proporcionan evidencias sobre el papel de los protrombolitos en la generación de lagunas costeras de diferentes regiones del NW de México, en donde las plataformas protrombolíticas y/o trombolíticas son un rasgo común. En Bahía Magdalena, se encontraron tapetes de cianofitas bajo desecación, conformados por *Microcoleus chthonoplastes* Thuret ex Gomont y sus vainas vacías remanentes junto con estructuras litificadas (trombolitos) cementados con micrita, considerada de origen biótico. Previamente propuesto como un proceso lagunar, ahora se sugiere que el desarrollo protrombolítico que conduce hacia la formación de lagunas costeras, ocurre en ambientes no lagunares con condiciones hidrológicas similares. No obstante, tal proceso se exacerba dentro de la laguna costera formada. Se sugiere también que el establecimiento de bosques de manglar es precedido por la formación de plataformas protrombolíticas que proporcionan un sustrato estable para mangles en lagunas costeras tropicales y subtropicales.

Palabras clave: Geomorfología, lagunas costeras, protrombolitos, tapetes de cianofitas.

INTRODUCTION

Microbial mats and pro-thrombolites. Coastal microbial mats extend hundreds of square meters over lagoon beaches in tropical and subtropical environments (Golubic *et al.*, 1999) forming dense, organic-rich sedimentary structures that frequently accrete above high tide (Stal, 2000). These microbial mats are formed mainly by cyanobacteria that trap and bind sediments, and resist erosion to a great extent, forming thus conspicuous living substrates in tropical coastal lagoons. Consequently their sediment stabilizing effect has been considered of great importance for coastal morphogenesis (Stal, 2000).

Extensive benthic mats formed by filamentous cyanobacteria occur in most of the intertidal and subtidal margins of the La Paz lagoon, B.C.S., Mexico (Siqueiros-Beltrones, 2006). These are mostly associated to soft, conglomerated (vertically accreted) mats and to more or less consolidated sediment platforms, which due to their rocky appearance with a greenish covering (Siqueiros-Beltrones, 2008) had been hitherto unnoticed. These may be platforms and/or fragments of assorted sizes resembling mudstone, but in all cases they occur as seaward hardground extensions. In the case of lithified structures, their clotted nature indicated that these were thrombolithic in nature (Siqueiros-Beltrones, 2008). Thrombolites have been defined as benthic biosedimentary structures generated by the entrapment, binding, and consolidation of sediments as result of the metabolic activity and growth of microorganisms, particularly cyanobacteria; unlike stromatolites do not show internal lamination (Charpy *et al.*, 1999; Stal, 2000; Shapiro, 2000). This most closely depicts the process we are currently investigating, inasmuch the platforms initially recorded from La Paz lagoon were described as pro-thrombolites, *i.e.*, non lithified sedimentary structures generated by the growth of cyanophyte mats, *i.e.* clotted sediments with inclusions of shell fragments, irregularly packed, surrounded by a sheet of active cyanobacteria (Siqueiros-Beltrones, 2008). Although some lack it because of prolonged exposure or for being covered by other sediments (Siqueiros-Beltrones *et al.*, 2009) many still characteristically show a conspicuous sheet of filamentous cyanobacteria, mainly *Microcoleus chthonoplastes* Thuret ex Gomont and *Lyngbya aestuarii* Liebman ex Gomont. Although other species are common, such as *Spirulina* sp., *Oscillatoria* spp., *Calothrix*, and unicellular forms: *Chroococcus* sp. and *Aphanotece* sp. (Siqueiros-Beltrones, 2008), much like in the reported cyanobacterial mats (García-Maldonado, 2005). Also, in spite of the periodical desiccation, as many as 150 diatom taxa thrive on the pro-thrombolite surfaces, mainly of mangrove affinity (Siqueiros-Beltrones, 2006). Some of the more consolidated platforms lacking a cyanobacterial cover strongly resemble the microbialithic structures from the Bahamas, as in Whitton and Potts (2000).

Living microbialites, including those in the Baja California peninsula, are important for the understanding of recent environmental changes, and because thrombolites and other microbialites are also represented in the ancient geological record, this information is critical for the understanding of past environments as well. In particular, pro-thrombolites forming today around the La Paz lagoon margins exert important changes in the overall geomorphological development of the area, including landscape changes and alteration of water flows and upper tidal limits (Siqueiros-Beltrones, 2008).

Geomorphology of coastal lagoons. Most coastal lagoons are closely related to the presence of a sand barrier or barrier islands. Nonetheless, the geomorphological mechanisms for the formation of barriers are not fully understood and their origin has been the subject of debates for more than a century. Several explanations or models have been proposed on sand barrier formation from which three theories are said to prevail (Kjerfve, 1994). One of them is the existence of low lying areas or spits, *i.e.*, extensions of beaches that protrude into a bay as a result of deposition of sediments carried by long-shore currents. Likewise, the formation of coastal lagoon barriers depends on sand supply, wave energy, and tidal fluctuations (Phleger, 1969). Yet, deposition alone does not imply permanence of the sediments, unless a cohesive agent is at play. Conspicuous cyanobacterial mats growing in coastal lagoon environments may play such a role. Hence, we propose the inclusion of a long-term biological factor into these theoretical models, as a mechanism of ensuring the stabilization of loose sediment (by trapping and binding) in spits and barriers.

La Paz lagoon in Bahía de La Paz, Mexico (Fig. 1) began forming around 6000 years ago by coastal transportation and deposition of sediments, eventually forming a sandbar, and transforming a primitive cove into the present coastal lagoon (Nava-Sánchez

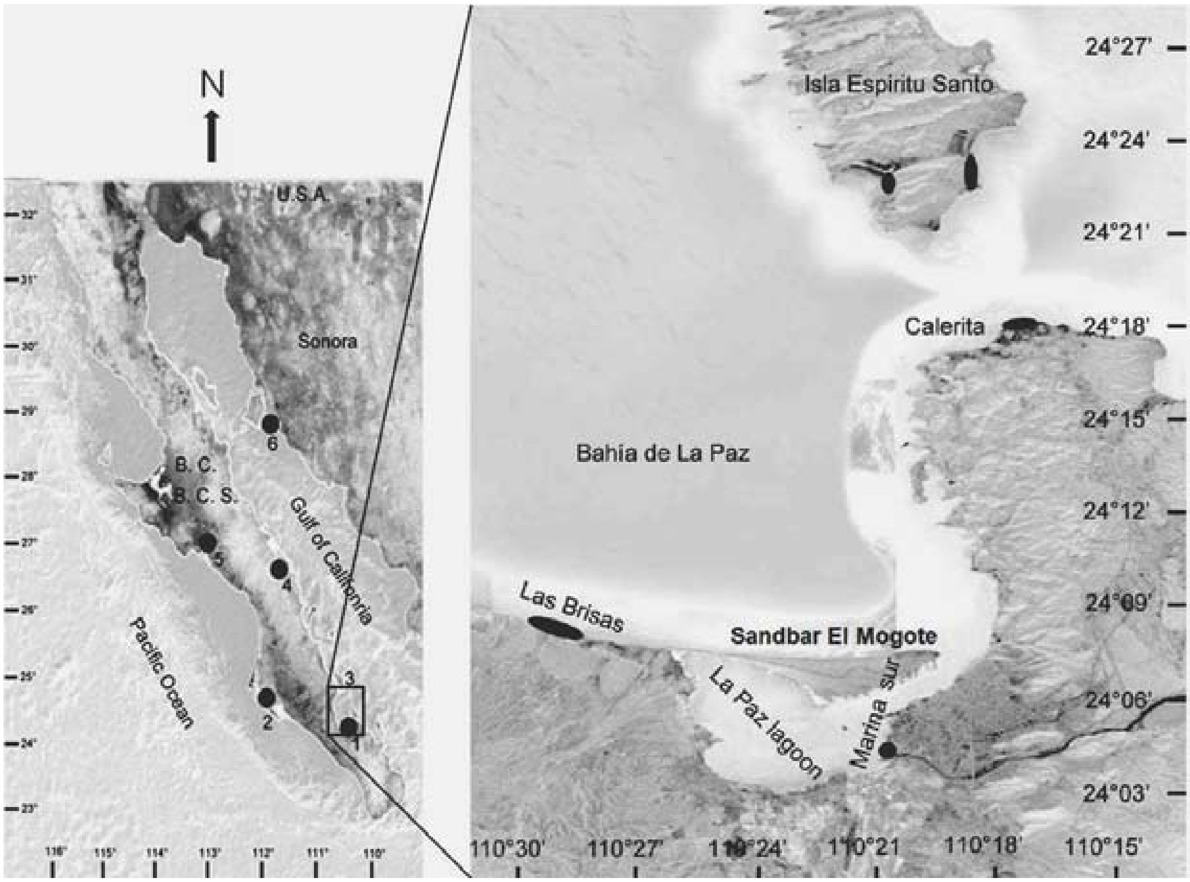


Figure 1. Sites with thrombolites and pro-thrombolites outcrops in the coasts of the Gulf of California and the west coast of B.C.S., Mexico. 1) Close up of sites in Bahía de La Paz, including Calerita and Isla Espíritu Santo; 2) Bahía Magdalena (San Carlos); 3) Isla San José; 4) Bahía Concepción; 5) Laguna San Ignacio; 6) Estero El Soldado, Guaymas, Sonora.

& Cruz-Orozco, 1989). Notwithstanding, the hypothetical spit proposed by the former authors needed to trigger-off and mantain the growth of the sandbar lacked a feasible origin. It was thus proposed that pro-thrombolithic growth might have defined the hypothetical spit where the armpit of the La Paz lagoon is defined. Through continuous growth, this provided a basement for the development of the sandbar El Mogote that transformed the primitive cove into the (Ensenada de La Paz lagoon (Siqueiros-Beltrones, 2008).

The very similar geomorphology of most coastal lagoons in the Gulf of California, also lead us to hypothesize that the process of formation involving pro-thrombolithic development in all cases could be the same. It was later suspected that the pro-thrombolithic platforms might have played and could still be playing an essential role in the geomorphological development of coastal lagoons in all the NW region of Mexico through seaward accretion of pro-thrombolites and bar formation. Additionally, recently gathered stratigraphic evidence suggested that pro-thrombolithic processes are responsible for the formation of the substrates around the La Paz lagoon (and probably others) supporting mangrove forests and human settlements (Siqueiros-Beltrones *et al.*, 2009).

According to the above hypothesis, in the margins of coastal lagoon cyanobacterial mats continue to evolve into conglomerated mats that generate unconsolidated pro-thrombolites (Siqueiros-Beltrones, 2008). Although previous mineralogical analysis of pro-thrombolites showed the presence of cementing microcrystalline calcite (micrite) these structures are unlithified and represent an intermediate stage between microbial mats and thrombolites. This substrate can be colonized by mangroves, which are common in tropical coastal lagoons. However, answers to the following questions are compelling, is this thrombolithic accretion process found exclusively in coastal lagoon environments? Can we confirm the transition from growing microbial mats to pro-thrombolites to thrombolites? Are thrombolithic structures the common substrate for mangroves?

First, we predicted that pro-thrombolites will not be found outside lacunar systems given their restriction to shallow waters and the requirement of coarse sediment flux for their formation, which is more active along the shore. However, comparisons of lacunar and non-lacunar environments in the Gulf of California are so far inexistent. Second, that the transition between conglomerated mats and thrombolites should be found somewhere in the intertidal margins, because coastal lagoon margins continue to accrete while microbial mats evolve into more consolidated pro-thrombolites and eventually into thrombolites. Third, the observation of mangroves growing on pro-thrombolites and thrombolites, suggests that these microbialites serve as the preferred anchoring substrate for mangrove seeds in tropical and subtropical coastal lagoons.

The aim of this study was to provide support on the proposed pro-thrombolithic nature of coastal ground and their relation to coastal lagoon formation and on the relationship between cyanobacteria mats, pro-thrombolites and thrombolites. Also, to show the dependence of mangrove recruits on cyanobacteria mats and pro-thrombolites as an anchoring substrate.

MATERIAL AND METHODS

Study area. Our observations comprise coastal lagoons in the NW region of Mexico. We particularly focused on the La Paz lagoon and Bahía Magdalena because the former has been more closely studied, and the latter because it is where the hypothesis that thrombolites and pro-thrombolites were to be found in other coastal lagoons was first contrasted. However, we also searched for said structures in Bahía Concepción (B.C.S), and Estero El Soldado (Guaymas, Sonora) (Fig. 1). A good account of the geological nature of the Baja California Peninsula coast flanking the Gulf of California is given in Johnson and Ledesma-Vázquez (1997).

The margins of the explored coastal lagoons are populated by marsh vegetation, mainly *Salicornia* spp. and three species of mangrove (*Avicennia germinans* (Linnaeus) Stearn, *Rhizophora mangle* Linnaeus and *Laguncularia racemosa* (Linnaeus) Gaertner) closely associated to the pro-thrombolithic grounds. These grounds are covered by sheaths of cyanobacteria and are associated with microbial mats located seaward, or landward exposed to desiccation among the mangrove and marsh vegetation.

In the La Paz lagoon, located in southeastern coast of the Baja California Peninsula, the black mangrove *Avicennia germinans* is the most common mangrove recorded although *Rhizophora mangle* (red mangrove) is also conspicuous, while *Laguncularia racemosa* (white mangrove) is scarce. Description (and other references) of this lagoon and the first record of pro-thrombolithic structures associated to mangroves are found in Siqueiros-Beltrones (2006, 2008). Likewise, in Bahía Magdalena lagoon located on the southwestern coast of the Baja California peninsula, the lagoon margins are densely populated by mangrove forests of the same three species, although much bigger, also closely associated to pro-thrombolites. But, unlike in the La Paz lagoon, *Laguncularia racemosa* is very common. Several sites were explored specifically around Puerto San Carlos where thrombolithic platforms were exposed and structures assumed to represent transitional stages between conglomerated mats and thrombolites were recorded landward among the mangrove trees.

Also, structures from non-lacunar sites such as in Las Brisas and Calerita along the coastline of southern Bahía de La Paz (Fig. 1) were recorded along vast extensions of exposed sandy beaches. There the vegetation consists mostly of macroalgae in both the intertidal, and in the subtidal along with many other fouling species that use the thrombolithic platforms or boulders as substrate. Besides, because lacunar-like environments are evident in the island coves in the southern Gulf of California, explorations were done at Isla Espíritu Santo and Isla San José where mangrove forests are well established.

Observation of pro-thrombolithic formations. Observations of pro-thrombolites, thrombolites, and conglomerated mat structures associated with mangroves carried out in the southern part of the Gulf of California came mainly from Bahía de La Paz, particularly La Paz lagoon. We added observations of structures located in the sandbar and from Marina Sur a previously unexplored site inside the lagoon (Fig. 1). These structures were found on the basis of the hypothesis that the pro-thrombolihtic process should be common throughout the inside margins of the lagoon (Siqueiros-Beltrones, 2008). Closer observations, plus sampling, were made in Bahía Magdalena on the western coast of B.C.S. All this was complemented with images from 2008 in other coastal lagoons in northeast B.C.S: Bahía Concepción, and from Estero El Soldado (Guaymas, Sonora) in 2010 (plus a recent slide from Estero Santa Rosa, Hermosillo, Son.), in the central Gulf of California. However, closer analyses for these localities are still pending.

Because lagoon-like environments are evident in the island coves in the southern Gulf of California, explorations were done at Isla Espíritu Santo and Isla San José where mangrove forests are well established. Additionally, observations on thrombolithic-like platforms and blocks outside lacunar environments in the Gulf of California are graphically documented to the north (Calerita) and northwest (Las Brisas) of the La Paz lagoon, inside Bahía de La Paz in the southern Gulf. In this case the null hypothesis stated that such structures would not be found inasmuch as the explored sites were not lacunar environments.

In March 2009 in San Carlos, Bahía Magdalena, we searched both for thrombolithic structures and transitional stages between cyanobacterial mats and thrombolites, *i.e.*, consolidated sedimentary structures with evidence of cyanobacteria remains, such as filament sheaths. We made direct observations of thrombolites, cyanobacterial mats and pro-thromboliths that we documented photographically. Also, in order to more closely compare this locality with the La Paz lagoon, samples of all structures were collected (at San Carlos) within an area of approximately 25 m^2 for microscopic analysis to identify the filamentous cyanobacteria covering the structures. And likewise for comparing sediment texture and mineralogy of the consolidated and soft structures with those described in Siqueiros-Beltrones (2008).

Microbiological observations. Wet mounts were prepared with samples from the surface of pro-thrombolites sampled in San Carlos. Portions of the samples were shaken with distilled water in essay tubes and subsamples recovered for observation (Siqueiros-Beltrones, 2008). Wet mounts were observed under phase contrast microscopy and photographed using Kodak 400 ASA film.

Analysis of thrombolithic and pro-thrombolithic structures. As previously described for the La Paz lagoon (Siqueiros-Beltrones, 2008), samples of consolidated and soft structures from San Carlos were examined to determine their degree of consolidation and for textural and mineralogical analysis; these included: a) fragment of semi-consolidated pro-thrombolite; b) isolated root like sedimentary structures; c) root-like structures associated to pro-thrombolite; d) soft desiccating mat associated to pro-thrombolite; e) soft isolated microbial mat. In order to examine the samples, textural analyses were made in six different ways: 1) A part was broken down by hand, and the analysis was conducted using a laser particle analyzer (LPA); 2) 15% HCl was added to a subsample to eliminate carbonated matter, and a textural analysis was done with the LPA; 3) This subsample was disintegrated by hand, and acetone and hexametaphosphate were added to remove organic matter and to preclude the cohesion between grains, respectively; texture analysis was done with the LPA; 4) This part was impregnated with epoxy to make a thin section, and the components were described under a petrographic microscope; 5) This subsample was disintegrated by hand, and its components were described under a stereoscope; 6) The subsample was treated with 15% HCl to eliminate carbonates; thin sections were examined under a petrographic microscope (Table 1).

RESULTS

Sediment and petrographic analyses of samples from San Carlos, Bahía Magdalena, show that both conglomerated mats and

Table 1. Processing and mineralogical composition of pro-thrombolithic samples collected in San Carlos, Bahía Magdalena, B.C.S. A) abundant, P) present, S) scarce, St) strong, W) weak, VW) very weak, MA) moderately abundant.

Sample		A	A1	A2	B	B1	B2	C	C1	C2	D	D1	D2	E	E1	E2
Process	Crumbled by hand		x			x			x			x			x	
	Impregnated	x			x			x			x			x		
	Treated with HCl			x			x			x			x			x
Equipment	Petrographic microscope	x		x	x		x	x		x	x		x	x		x
	Magnifying glass		x			x			x			x			x	
Hardness	Semi-consolidated	x	x	x	x	x	x	x	x	x						
	Non-consolidated											x	x	x	x	x
Organic mater												P	A	A	A	A
Minerals	Quartz	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Phelderspate-plagioclase	P	P	P			P	P		P				P		
	Amphibolites		P			P			MA	MA		P		MA	P	
	Hornblend						A	P		P	P		P			p
	Olivine	P			P	P								P		
	Phosphate oolites	P	P	P		P		P	P	P	P	P			P	
	Opaque minerals	P											P			p
	Biotite						P						P			P
Matrix	$CaCO_3$ microcrystals		A			A			S							
	Microsparite	A						S								
	Micrite				P											
Reaction to HCl			St						W			VW			VW	
Fiber												P			A	

semi-consolidated pro-thrombolites are very similar in their mineralogical composition. All samples carry abundant quartz, more or less abundant hornblende, and traces of feldspars, phosphorite oolites, olivine, and shell fragments. The semi-consolidated samples showed grains of microcrystalline texture, most likely micrite (carbonate or phosphate) surrounded by decaying organic matter. The cementing micrite, however, detached when the sample was crumbled by hand (Table 1). In most samples the degree of grain selection is poor indicating an ample range in grain size, which according to their frequency distribution leans toward the fine size grains; between 40 and 60% is fine and very fine sand, and 30 to 45% is medium and coarse sand (Table 2), which reflect the low energy conditions of the sampling area in San Carlos.

Description of thrombolithic and pro-thrombolithic formations in lacunar and non-lacunar environments. Consolidated pro-thrombolithic blocks of 50 cm high (approx.) were discovered at Marina Sur, in the La Paz lagoon, associated to *Avicennia germinans*. These blocks were broken-off from a platform structure, and those more exposed to wave energy appeared eroded, particularly around the lower part (Figs. 2-6) roughly resembling the bun shaped stromatolites of Shark Bay, Australia, albeit not with the consolidation (lithification) and separation, probably due to erosion, of the latter which are millions of years old versus the few hundreds of years of the former. These showed the same clotted matrix and sheet cover as other pro-thrombolithic platforms described earlier for the lagoon (Fig. 6).

In non-lacunar environments we observed similar though lithified sedimentary structures at Las Brisas and Calerita. In the former, extensive thrombolithic platforms occurred along the intertidal area with broken off blocks that were located in the lower intertidal area (Figs. 7-9) and showed heavy fouling. In Calerita, as in Las Brisas, platforms were also found and blocks were broken off due to wave erosion under the platforms. In this case separate episodes could be identified based on the two observed strata in this location (Fig. 10); the platforms exhibited perforations that could be interpreted as remains of mangrove roots being anchored in the once pro-thrombolite (Figs. 11-12).

The above observations oblige us to reject our hypothesis that thrombolithic structures would not be found in a (modern) non-lacunar environment. This raised the question to whether these areas presented coastal lagoon environments in the geological past or not. However, the assumed association of pro-thrombolites to mangroves may be supported by fossil-like structures from El Mogote in the La Paz lagoon. These complex formations derived from the interaction between dead mangrove root systems and pro-thrombolites (Figs. 13-15), are most likely rhizoliths.

The exploration for thrombolithic and pro-thrombolithic structures in the southern gulf islands, Espíritu Santo and San José, showed contrasting stages of development. In the former, thrombolithic platforms of different appearances were conspicu-

Table 2. Percentages of grain mean size and standard deviation of sediments in the pro-thrombolithic samples A-B (crumbled by hand and (1) Impregnated) from San Carlos, Bahía Magdalena, B.C.S.

	Phi (ϕ)	A	A1
Granules	1-2	3.59	0.00
Very coarse sand	–0.75-0	18.72	0.62
Coarse sand	0.25-1	16.95	7.30
Medium sand	1.25-2	28.35	36.90
Fine sand	2.25-3	23.15	41.55
Very fine sand	3.25-4	3.56	7.07
Silt-clay	4.25-14.5	5.69	6.56
	ϕ	B	B1
Granules	1-2	4.92	0.00
Very coarse sand	–0.75-0	25.76	6.97
Coarse sand	0.25-1	15.60	9.28
Medium sand	1.25-2	20.82	30.73
Fine sand	2.25-3	18.96	34.19
Very fine sand	3.25-4	4.56	6.16
Silt-clay	4.25-14.5	9.40	12.78
	ϕ	C	C1
Granules	1-2	0.25	0.21
Very coarse sand	–0.75-0	3.43	5.32
Coarse sand	0.25-1	4.84	1.65
Medium sand	1.25-2	25.83	28.99
Fine sand	2.25-3	44.10	50.05
Very fine sand	3.25-4	7.03	6.31
Silt-clay	4.25-14.5	14.59	7.45
	ϕ	D	D1
Granules	1-2	0.00	5.06
Very coarse sand	–0.75-0	0.00	1.30
Coarse sand	0.25-1	26.54	29.01
Medium sand	1.25-2	56.11	51.12
Fine sand	2.25-3	9.64	7.72
Very fine sand	3.25-4	7.68	5.69
Silt-clay	4.25-14.5		
	ϕ	E	E1
Granules	1-2	0.00	0.00
Very coarse sand	–0.75-0	1.25	1.29
Coarse sand	0.25-1	4.28	8.71
Medium sand	1.25-2	31.82	34.92
Fine sand	2.25-3	35.58	38.04
Very fine sand	3.25-4	6.40	8.52
Silt-clay	4.25-14.5	20.71	8.48

Figures 2-7. Microbial structures located in the Bahia de La Paz, B.C.S., Mexico, mainly inside the lagoon: 2) Extensive cyanobacterial mats (far view) and pro-thrombolithic platform (close view) in Centenario SW margin of La Paz lagoon; 3) Fragmented pro-thrombolite platform supporting mangroves (*Avicennia germinans*) in Marina Sur; 4) Eroded platform showing channels in Marina Sur; 5) Detached blocks with eroded bases in Marina Sur that remind of the bun shaped stromatolites of Shark Bay, Australia; 6) Structures showing the same clotted matrix and sheet cover as other pro-thrombolithic platforms in Marina Sur; 7) Non-lacunar thrombolithic blocks and platforms showing smooth surfaces covered with cyanobacteria at Las Brisas north outside of the lagoon.

ous in various sites, either as exposed (Fig. 16) or protected (lacunar) platforms (Fig. 17), and lithified bridge-like structures (Fig. 18). In Isla San José, however, pro-thrombolithic formations seemed incipient, associated to thick microbial mats (Figs. 19-20). Further exploration is required at Isla San José inasmuch formation of sandbars, very similar to El Mogote in La Paz lagoon, suggest past pro-thrombolithic activity in several sites.

In the northern part of B. C. S incidental observations were done in Bahía Concepción specifically at El Requesón. There, thrombolithic platforms showing different stages of development were associated to other geological processes besides those of sedimentary nature (embedded boulders). We recorded a platform of a muddy appearance located landward and a more defined (cemented) one, albeit associated to a *Laguncularia racemosa* specimen (Figs. 21- 22).

In order to gather information on the proposal that prothrombolithic ground formation influencing the geomorphology of coastal lagoons occurs all throughout the Gulf of California and the rest of the Mexican NW, we explored the coast of Sonora. The closest and more recent observations to these lagoons were done at Estero El Soldado in Guaymas, where the same conglomerated formations were noted along with thrombolithic-like platforms, also associated to mangroves (Fig. 23). This initiative however came from viewing a slide from Estero Santa Rosa, Sonora that showes Seri Indians seating on prothrombolithic blocks (Fig. 24). Albeit samples from these sites are not yet available and sedimentological and other direct examinations are pending, the image shows Seri natives seating on what we recognized as thrombolithic blocks in a mangrove environment.

In San Carlos (Bahía Magdalena) uncovered thrombolithic

Figures 8-13. Thrombolithic formations in different localities of Bahía de La Paz, B.C.S., Mexico: 8) Blocks in the intertidal covered by green macroalgae at high tide at Las Brisas; 9) Thrombolithic formation in the intertidal covered by green macroalgae during low tide at Las Brisas; 10) Non-lacunar thrombolithic platforms where two separate episodes can be identified based on the two layers of beach-rock platforms at Calerita; 11) Thrombolithic platforms showing perforations at Calerita; 12) Close up of perforations in thrombolithic blocks at Calerita ; 13) Fragile rhizolith-like structures in the lower intertidal of El Mogote, La Paz lagoon.

structures (Fig. 25) may be observed in the beach areas free from mangrove cover, appearing as platforms limiting the sandy areas. Their fragmentation to different degrees is evident. In the mangrove areas dense microbial mats are conspicuous, closely associated to the *Laguncularia racemosa* root systems and, just behind the mangrove line, evidences of the transition from mat to pro-thrombolith can be found. Extensive soft discolored mats (Fig. 26) are found fused with the consolidated thrombolithic structure (Fig. 27).

Microscopic examination of the above samples however revealed mostly sediments together with empty sheaths and drying filaments mainly of *Microcoleus chthonoplastes* that are also common. However, green (live) filaments of *Microcoleus chthonoplastes* (Figs. 28-30) and *Lyngbya aestuarii* are less frequent. The scaffold function of the microbial mat is evidenced by the presence of soft bridge-like structures (Fig. 31) as the (lithified) one in Isla Espíritu Santo (Fig. 18), in which empty sheaths are common along with scarce live filaments. The presence of both empty sheaths and green filaments suggests that either new colonization is occurring or that, as it has been observed with living stromatolites, a live part remains from the original conglomerate mats that originated the thrombolite. This would apparently

Figures 14-19. Pro-thrombolithic structures in different localities of B. C. S.: 14) Extensive platform with thick root like formations in the upper intertidal of El Mogote; 15) Lithified platform with fragile rhizolite system in the upper intertidal of El Mogote; 16) Thrombolithic platform on the exposed east coast intertidal of Isla Espíritu Santo; 17) Thrombolithic platforms in a cove on the west coast of Isla Espíritu Santo; 18) Bridge-like thrombolithic structures (ca. 25 cm) adjacent to mangroves on the west coast (San Carlos, B.C.S.); 19) Incipient pro-thrombolith at Isla San José.

support the proposed hypothesis that a transitional structure existed. However, this has to be more accurately stated, because the transitional structures between mats and thrombolites are pro-thrombolites, while in the observed structures they were past the pro-thrombolithic stage (more consolidated) and mats in which cyanobacterial sheaths are still present and thus represent separate geological events.

Finally, concerning our question: are thrombolithic structures the common substrate for mangroves? Our observations show that both mangrove recruits and trees were only anchored either in conglomerated mats or in thrombolithic/pro-thrombolithic outgrowths but not in the bordering sand (Fig. 32-36). Our hypothesis is thus consistent with our observations in all the sites, *i.e.*, mangroves use the preformed structures by cyanobacterial mats (conglomerate mats, pro-thrombolites, thrombolites) as fixing substrate. Nonetheless, mangrove trees were seen anchored on other non-thrombolithic rocky substrata, as in Isla SanJosé where incipient pro-thrombolithic formations were recorded (Figs. 19-20).

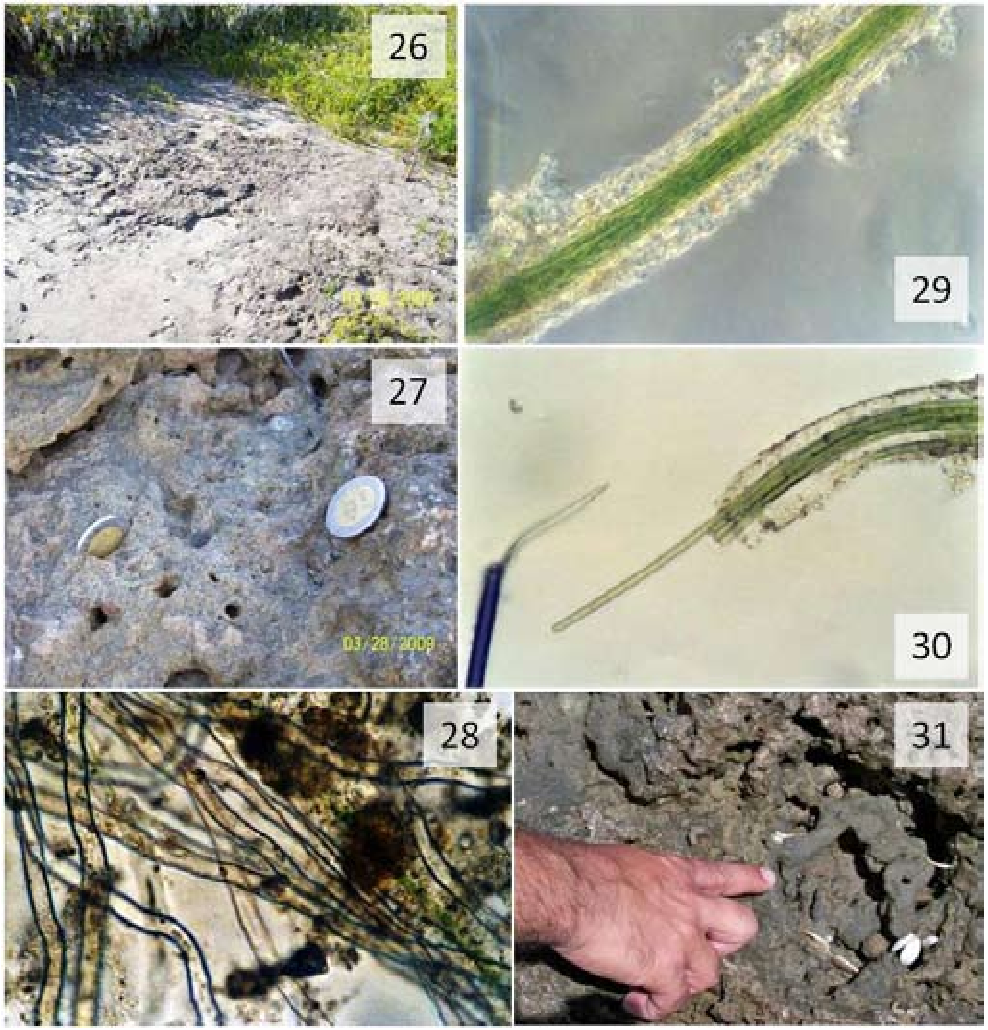
DISCUSSION

The above description for the San Carlos samples does not depart from the one given earlier for thrombolithic structures of the

Figures 20-25. Pro-thrombolithic structures in other localities of the Gulf of California, Mexico: 20)Thick cyanobacterial mat from the intertidal of Isla San José; 21) Pro-thrombolithic muddy platform at El Requesón, Bahía Concepción; 22) Lithified thrombolithic platform and *Laguncularia racemosa* specimen; 23) Thrombolithic platform at Estero El Soldado, Sonora; 24) Seri natives seating on a thrombolithic block in Estero Santa Rosa, Sonora; 25) Thrombolite platform and fragments in the upper intertidal area of San Carlos beach, Bahía Magdalena, west coast of B.C.S.

La Paz lagoon (Siqueiros-Beltrones, 2008) where environmental conditions are much alike. Mineralogical analyses indicate that grains from San Carlos are probably formed under marine conditions and the acid treated samples show a similar degree of selection indicating that they come from sites under similar (low) energy conditions.

The common denominator is the presence of micrite which we expected to be present or abundant in consolidated to lithified structures, whereas most of our samples were non-lithified pro-thrombolithic structures. Although the means by which microbial communities mediate the precipitation processes of micro- crystalline $CaCO_3$ remain unclear and are subject to debate and speculation (Kazmierczak *et al.*, 1996; Paerl *et al.*, 2001), it has been determined that huge amounts of micrite may be produced by precipitation mainly by cyanobacteria in marginal marine marshes (Tucker & Wright, 1990) and its presence is consistent with the shallow (intertidal) marine environment. Thus we have assumed a biogenic origin for the identified micrite that may be associated to the microbial mat photosynthesis.



Figures 26-31. Early stages of pro-thrombolithic development in the west coast of B.C.S., Mexico: 26) Soft conglomerating cyanobacterial mats drying in the intertidal area at San Carlos beach, B.C.S, alongside the "transitional" pro-thrombolithic formation; 27) Transition from soft conglomerated mats (embedded coin) fused to consolidated pro-thrombolithic formation (laid coin) in San Carlos; 28) Photomicrograph of empty *Microcoleus chthonoplastes* sheaths acting as scaffold in the transitional pro-thrombolite mat from San Carlos in Bahía Magdalena (200x); 29) Filament of *Microcoleus chthonoplastes* from San Carlos showing thick sheaths (400x); 30) Trichome from *Microcoleus chthonoplastes* filament at 630x from San Carlos; 31) Soft bridge-like pro-thrombolithic mat (ca. 20 cm) structure (scaffold) at San Carlos.

In the above scenario, activity would continue as long as a cyanobacterial cover remained on the conglomerated sediment platforms (prothrombolite) that is subject to tidal flooding, in which case the precipitated micrite would be forced through the cyanobacterial mesh during ebb tide, depositing between the sand grains and gradually cementing them.

A report by Holser *et al*. (1981) at Laguna Ojo de Liebre (Guerrero Negro, B.C.S.) supports our observations that the main cyanobacteria species *Microcoleus chthonoplastes* and *Lyngbya aestuarii* involved in pro-thrombolithic processes are the same; these taxa are important components of microbial mats in several parts of the La Paz lagoon (García-Maldonado, 2005) and particularly those associated to pro-thrombolites (Siqueiros-Beltrones, 2008). Moreover, the former species is known to be the dominant taxon in marine intertidal microbial mats worldwide (Stal *et al*., 1985). Although present at San Carlos, diatoms were not examined, and further floristic analyses were not done for the cyanobacteria inasmuch our sole interest was focused on confirming the dominant taxa involved in the pro-thrombolithic process.

Microbial structures are common along the Baja California Peninsula, including stromatolites (Miranda-Avilés *et al*., 2005) and hypersaline mats (Holser *et al*., 1981; Horodysky & Von der Haar, 1975; Horodysky, 1977), which are among the most studied in the world (Stal, 2000). Logan *et al*. (1964) and Altermann *et al*.

Figures 32-36. Associations between mangroves and different stages of thrombolite formation in B.C.S., Mexico: 32) Black mangrove (*Avicennia germinans*) anchored on thrombolihtic platform (La Paz lagoon; 33) White mangrove shrub (*Laguncularia racemosa*) anchored on pro-thrombolithic platform (El Mogote, La Paz lagoon); 34) Recruits of red mangrove (*Rhizophora mangle*) anchored in soft conglomerated mat at San Carlos; 35) Recruits of red mangrove (*Rhizophora mangle*) anchored in thrombolith outcrop at San Carlos; 36) *Rhizophora mangle* recruits anchored in thrombolithic platform surrounded by sand with no recruits at San Carlos.

(2006) have suggested that during the Pre-Cambrian, stromatolites and hence microbial mats had covered large areas. These may be represented by rocky ground far from the coast and living stromatolites in the intertidal, but also by extensive (non consolidated sediment) pro-thrombolithic platforms and trombolites in coasts. Therefore, extensive microbial mats such as those shown in Stal (2000) and here in figure 2 may have developed into conglomerated mats and pro-thrombolithic ground that eventually was to be occupied by human settlements or mangroves (Siqueiros-Beltrones *et al.*, 2009). Thus, the seaward development of spit-like pro-thrombolites would lead eventually to costal lagoon formation, but their hypothetic role in the geomorphology of coastal lagoons had not been proposed until recently (Siqueiros-Beltrones, 2008).

The above observations show that the described process occurs throughout the coasts of the Gulf of California and NW

Mexico both in lacunar and non-lacunar environments. The non-lacunar thrombolithic platforms observed indicate that, although thrombolithic formation is favored by the conditions established by the lacunar environment, it also shows that very similar (low energy and shallow) non-lacunar conditions would have initially promoted pro-thrombolite formation. Said process is further enhanced within the formed coastal lagoon. We have recently observed that similar non-lacunar thrombolithic platforms and pro-thrombolithic grounds are common off the coast of Yucatán, Mexico. Most likely, this process occurs in other parts of the world, contributing to the generation and eventual filling of costal lagoons and the formation of coastal terrains as depicted in Figure 37. Evidence for this process was generated by exploring excavations and analyzing sediment cores from La Paz lagoon coast (Siqueiros-Beltrones *et al*., 2009).

Previous observations have suggested that the role of mangroves as sediment traps that eventually cause ground formation (Dawes, 1981; Kathiresam, 2003) is a preexisting process that is accelerated by mangroves after colonizing suitable areas (Woodroffe, 1992). Our study, provides observations supporting that ground formation is initially carried out by cyanobacterial mats through binding, stabilizing, and clotting sediments, leading to the development of pro-thrombolithic platforms, and that these substrates are opportunistically colonized by mangrove recruits, as depicted in figures 32-36 that show no mangrove recruits off the microbial mats or off the microbialites. Plus, although mangrove recruiting has been observed to occur on other type of rock where mangrove trees thrive, in the costal lagoons we have surveyed, both mangrove recruits and trees are only observed anchored either in conglomerated mats or in thrombolithic/pro-thrombolithic outgrowths but not in the sand. Furthermore, accreting mats (conglomerated) develop extensively in the lagoon beaches were mangroves have not yet colonized (Fig. 2) though we have observed ephemeral recruiting on them in La Paz lagoon. The above supports our hypothesis that ground formation leading to island formation and shoreline extension hitherto attributed to mangrove forests (Dawes, 1981) that "claim land from the sea" (Woodroffe, 1992) is actually initiated by microbial mats, and continues through pro-thrombolithic growth, and is only later colonized by mangroves. The past occurrence of this process is, according to our hypothesis, recorded here geologically by the rhizoliths (Figs. 13-15) and in Siqueiros-Beltrones (2008); much like the ones described by Johnson *et al*. (1997) in the area of Bahía Concepción close to El Requesón, B. C. S.

Based on the above along with reports of pro-thrombolites from Laguna San Ignacio in the western coast of the Baja California peninsula (Siqueiros-Beltrones *et al*., 2008), and the observations in Bahía Magdalena we further support the hypothesis that microbial mats through pro-thrombolithic ground formation may have promoted the generation of coastal lagoons throughout NW Mexico. Thus, as more information becomes available, Lovelock´s (1979) assumption "let us now make the bold speculation that (coastal) lagoons formed as a consequence of the presence of life in the sea" comes into focus with prophetic connotation.

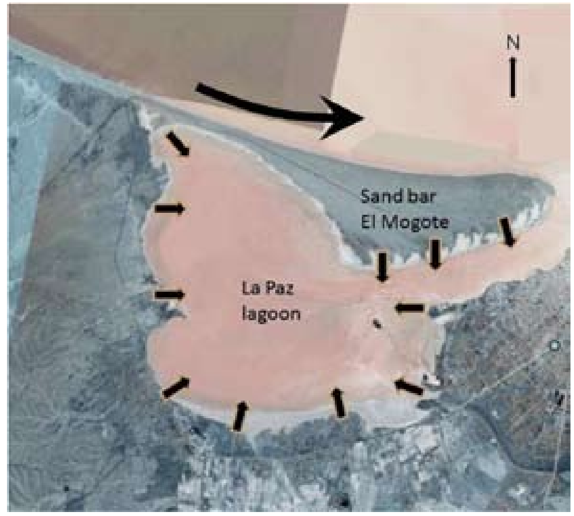


Figure 37. La Paz coastal lagoon in the southern Baja California peninsula. Large arrow indicates the growth of the sandbar along approximately 6000 years. Small arrows indicate pro-thrombolithic accretion along the internal margins of the lagoon, based on recorded platforms and extensive cyanobacterial mats.

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