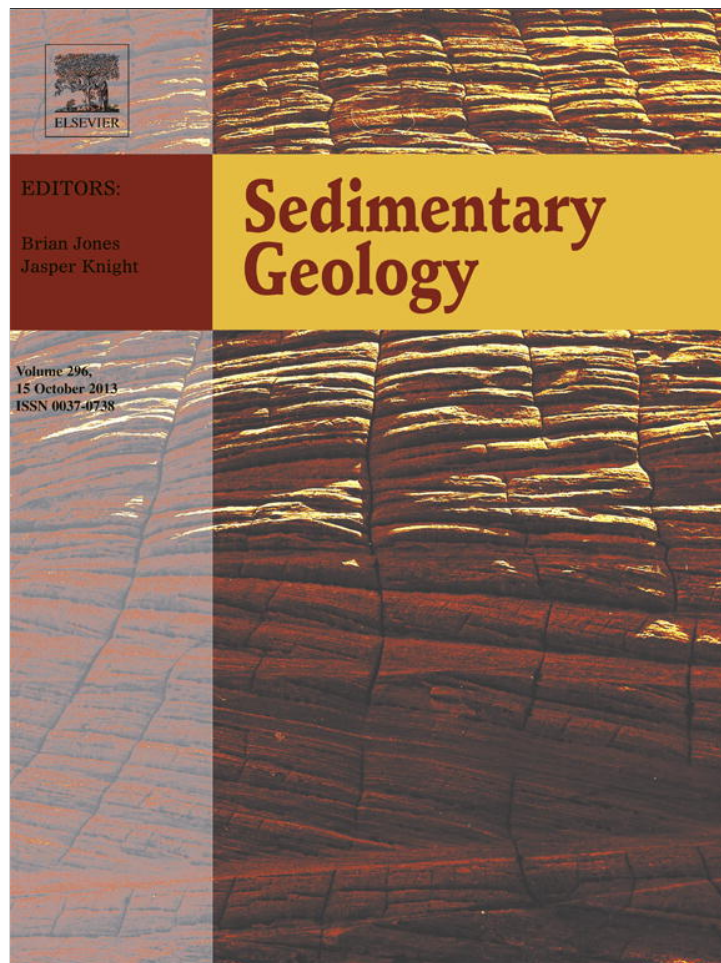


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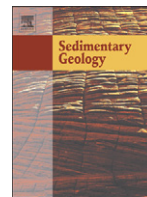
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Microbially-induced sedimentary structures (MISS) as record of storm action in supratidal modern estuarine setting



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ABSTRACT

One of the aims of tidal sedimentology in recent years is to find signatures in the stratigraphic record that help in recognizing basic ancient tidal processes. The present study was carried out on the supratidal zone of the middle Bahía Blanca estuary which is colonized by extensive microbial mats. The purpose of the study was to relate the tidal and wave energy with the microbially-induced sedimentary structures (MISS) present in the tidal flat. The energy reaching the area was quantified by tidal and wave records, while MISS were simultaneously recognized and described after a strong storm event. The MISS and the microsequences of sediments in vertical cross-sections of the tidal flat were considered as tidal signatures over a supratidal zone, when high-tide in severe energy conditions can reach the zone. This paper contributes to the understanding of physical sedimentary parameters that control the modification of microbial structures in modern siliciclastic regimes and that, in turn, can aid in the reconstruction of ancient hydraulic settings.

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1. Introduction

Some of the most important processes in estuarine environments involve tidal currents, which are responsible for sediment deposition and erosion (Wang, 2012). Additionally, wave action during storms can have a strong influence on sediment transport. However, as wave action is attenuated by friction toward the inner sections of an estuary, the sedimentation regime becomes tide-dominated. Much of the sedimentologic research in the past decades has focused on finding siliciclastic sediments laid down by tidal currents in modern and ancient deposits (Davis, 2012). In that sense, Klein (1971, 1998) proposed the term "tidalite" as a new process-sedimentary facies to describe the action by which estuarine sediments are deposited by tidal currents. Thus, the term "tidalite" is now applied to all sediments and sedimentary structures that have accumulated under the influence of tides (Davis, 2012). A thorough explanation of the influence of tidal cycles in sedimentation patterns was presented by Kvale et al. (1995), Kvale (2006, 2012), who considered the combined gravitational attraction of the sun and the moon, besides changes in the moon and Earth's orbits.

Tidal sedimentation processes encompass a wide range of marine settings, from the deepwater subtidal shelf to intertidal flat environments.

Likewise, a variety of sedimentary features known in modern intertidal environments are also common in sedimentary rocks. The supratidal zone, inundated only during the highest (in syzygy) and extraordinary storm-tides, also contributes with tidal signatures that permit the recognition of tidal influences (Bridge and Demicco, 2008). Moreover, Schieber (2004) emphasizes that the preservation of these sedimentary structures may be promoted by the presence of microbial mats in this setting, which supply cohesion and cementation. Microbial mats and biofilms have a significant influence on the response of sediments to hydraulic dynamics of waves and currents (Noffke, 2010) due to their sediment-stabilizing effect or "biostabilization" (sensu Paterson, 1994). The activity of eukaryotic microbes, cyanobacteria and bacteria protects the seafloor against erosion. However, the interaction of benthic microorganisms with physical sediment dynamics has been long underestimated (Noffke and Patterson, 2008). Microbial mats develop at sites of quiet hydraulic conditions and at the same time, their presence raises the erosional sediment threshold coefficient, the "biostabilization" effect defined by Patterson (1994). Therefore, microbially-induced sedimentary structures (MISS sensu Noffke et al., 2001) can tolerate an increase in tidal and wave energy.

The middle zone of Bahía Blanca estuary is characterized by extensive microbial mats in the upper intertidal and lower supratidal zones. Cuadrado and Pizani (2007) recorded human footprints that were being preserved during several months, probably due to the presence of authigenic minerals that enhance this preservation (Cuadrado et al.,

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2012). The evolution of the microbial mat in the temperate estuary was studied (Cuadrado et al., 2011) and also the relationship with seasonal changes and physical variables and the resulting sedimentary structures (Pan et al., 2013a).

The present study was carried out in Puerto Rosales, located in the middle Bahía Blanca estuary. The purpose of this study was to relate tidal and wave energy to some of the MISS present in the supratidal flat. The energy reaching the area during storm events was quantified by tidal and wave records, while MISS under these conditions were simultaneously recognized and described. Understanding the physical sedimentary parameters that control the formation and modification of microbial structures in modern siliciclastic regimes can aid in the reconstruction of hydrodynamic in ancient settings, taking place in early sedimentary rocks.

2. Materials and methods

2.1. Description of the study area

The Bahía Blanca estuary, located in southern Buenos Aires province, Argentina (Fig. 1), is subject to a mesotidal semidiurnal regime, with a mean tidal range from 2.5 m at the mouth to >4 m at its head. Perillo and Piccolo (1991) established that the Bahía Blanca estuary behaves hypersynchronously as the tidal range and tidal current amplitudes increase headward. Tidal currents are reversible with maximum velocities $\sim 1.3 \text{ m s}^{-1}$ at the surface and maximum vertically-averaged values of 1.2 and 1.05 m s^{-1} for ebb and flood conditions, respectively (Cuadrado et al., 2005). They are responsible for the formation of a dune field characterized by very large dunes ($H > 4 \text{ m}$, and $L > 100 \text{ m}$) in the main channel (Gómez et al., 2010). In the adjacent shoreline, in Puerto Rosales (Fig. 1), extensive tidal flats are exposed during ebb tide.

The study was performed at the tidal flats located at Puerto Rosales ($38^{\circ}55'30'' \text{ S}$; $62^{\circ}03'00'' \text{ W}$) where the upper intertidal and supratidal zones are colonized by microbial mats. The intertidal area is vegetated by the cordgrass *Spartina alterniflora*, while patches of *Sarcocornia ambigua* are distributed on the supratidal zone. The cordgrass acts as a shield that protects the upper tidal flat from deposition or erosion, promoting a low sedimentation rate and favoring the colonization of benthic microbial communities that form biofilms and microbial mats (Cuadrado et al., 2011), which are dominated by the filamentous cyanobacteria *Microcoleus chthonoplastes* and subordinately, pennate diatoms (Pan et al., 2013b).

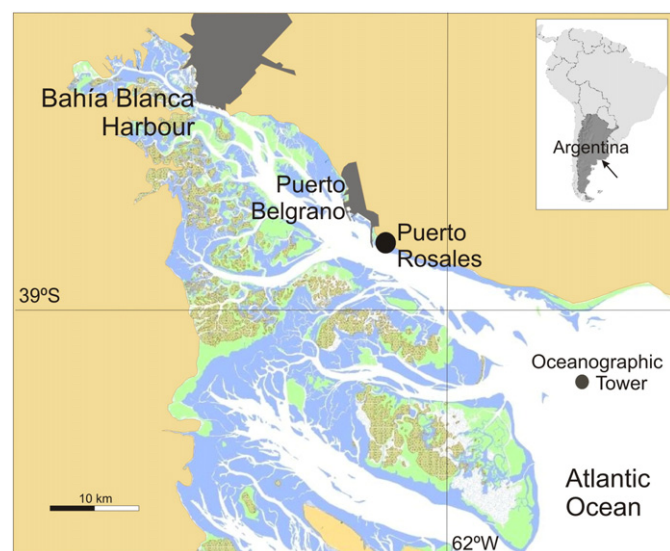


Fig. 1. Location of the study area within the Bahía Blanca Estuary, SW Atlantic Ocean.

Local winds from a NW direction generate waves with short wavelengths and periods of less than 6 s. However, during storm conditions (with prevailing strong southern winds), oceanic waves enter the estuary and reach the study site at Puerto Rosales. Wave height, measured in the Oceanographic Tower at the entrance of the estuary (Fig. 1) is 0.6 m on average, decreasing to 0.3 m in Puerto Rosales due to wave refraction and attenuation (Nedeco-Arconsult, 1983).

2.2. Methodology

Tidal height data were obtained from a tidal gauge at Puerto Belgrano located 4 km toward the inner portion of the estuary from the study area (Fig. 1). Flooding of the supratidal zone was estimated after tidal height. The wave height in conjunction with wind parameters (speed and direction) was measured at the Oceanographic Tower in the estuary entrance. The data analysis comprised a series from May to November 2010. Additionally, an area of 50,000 m^2 of tidal flat was routinely surveyed for microbially-induced structures on monthly campaigns.

In order to monitor sedimentation patterns on the tidal flat at Puerto Rosales, an artificial rough substrate (a $15 \times 15 \text{ cm}$ ceramic tile) was placed on the sediment surface during May 2010, similarly as the method used by Pasternack and Brush (1998). It was surveyed monthly, attending to changes in sediment deposition and erosion. Despite the rugosity of its surface, there must be a difference between microbial mat growth on the tile surface and the natural substrate. Nevertheless, the analysis of microbial colonization between lapse-time periods can provide some insights into mat-development and erosional processes. These facts, in turn, can be related to energy conditions.

3. Results

3.1. Hydrodynamics

Wave heights were $< 0.5 \text{ m}$ when wind velocity was $< 40 \text{ km h}^{-1}$. On the contrary, when the NNW wind reached velocities $> 40 \text{ km h}^{-1}$, waves reached 1 m height (green columns in Fig. 2). In those cases, the supratidal area was rarely covered during high tide (see Fig. 2 in Cuadrado et al., 2012). In contrast, when wind direction at the mouth of the estuary corresponded to that of the longer fetch (SE direction) and wind velocities were $> 40 \text{ km h}^{-1}$, waves reached more than 2 m height (yellow column in Fig. 2). Similar results were achieved under strong winds ($> 40 \text{ km h}^{-1}$) coming from the SW. In this situation, wave heights reached about 3 m after several days of strong winds (gray columns in Fig. 2, see July) and the supratidal area was submerged for several hours during consecutive high tides.

The strongest storm in 2010 occurred in July when a high speed wind ($> 40 \text{ km h}^{-1}$, and up to 70 km h^{-1}) from the SW blew for several days, creating waves of 2–3 m height. Under these circumstances, seawater reached the supratidal area (gray frame in Fig. 3). In particular, the month of July 2010 (corresponding to Austral winter) comprised the highest frequency of inundation of the supratidal area by consecutive high tides (Fig. 4).

3.2. Microbially-induced sedimentary structures (MISS)

After the July storm, several new MISS were found in the supratidal area of the study site. Among the erosional features, a few depressions of some dm in diameter, termed *erosional remnants and pockets* by Noffke and Krumbein (1999) were formed (Fig. 5A). These structures present a specific surface morphology that forms from the erosion and destruction of a microbial mat-covered and biostabilized tidal surface during high energy conditions (Gerdes et al., 1993; Noffke, 1999). The mat-protected and flat-topped rises of several cm in height are called *erosional remnants* (Noffke et al., 1997). The erosional pockets are irregular-shaped depressions where the sediment, uncolonized by

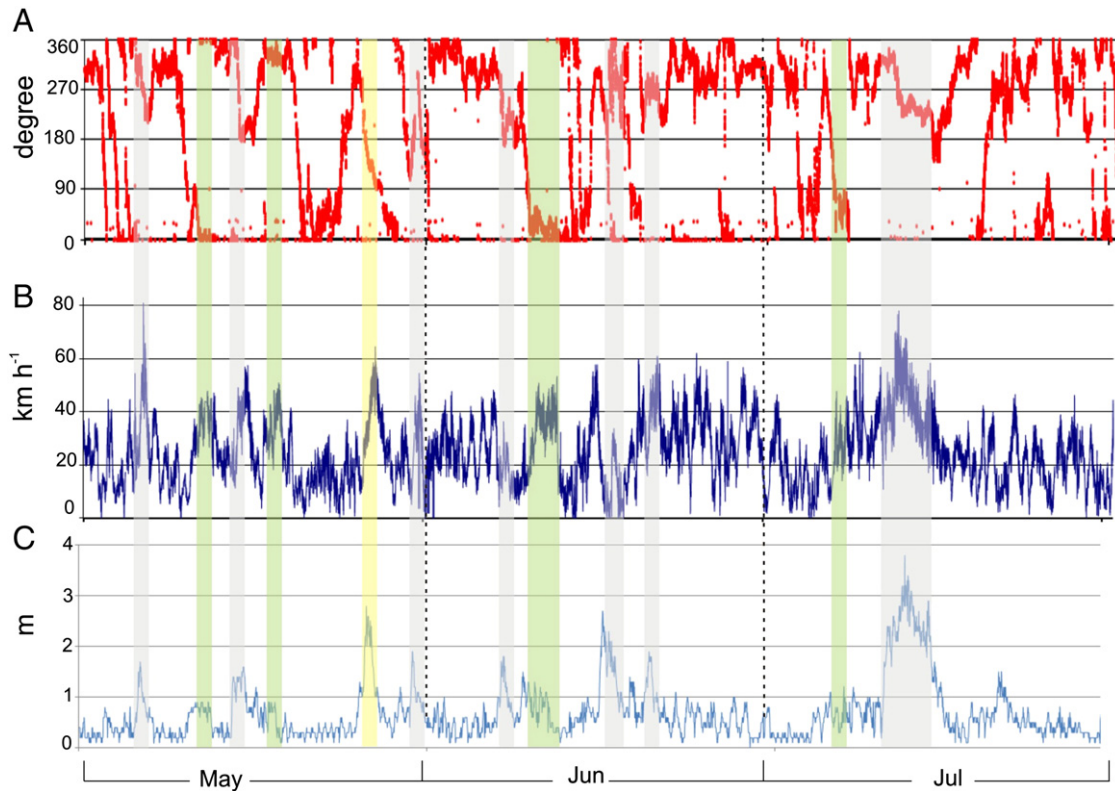


Fig. 2. Meteorological and wave parameters measured between May and July, 2010. (A) Wind speed (km h^{-1}) and (B) direction (degree from North). (C) Wave height (m). All parameters were measured at the Oceanographic Tower located at the entrance of the estuary (see Fig. 1).

microorganisms, shows ripple marks (Fig. 5B). The prevailing orientation of ripple mark crests indicates the direction of the flood current. This means that sediments in these parts of the tidal surface are still mobilized, in contrast to the raised, immobile areas (Noffke et al., 1997; Noffke, 1999). The sharp edges defining the depressions indicate a high level of biostabilization (Noffke and Krumbein, 1999; BS I sensu Noffke, 2010), associated with the development of epibenthic microbial mats.

Due to high energy currents and waves, *torn and flipped-over mats* (Fig. 5C, D, E) were also found. These are features that reflect a complete inversion of the mat-edges (Eriksson et al., 2007), and correspond to type II mat curls according to Noffke (2010). The formation of these

structures may be favored by pre-existing cracks (Fig. 5C), or by mechanical tearing of the mat (Fig. 5D). When formed, and under continuous erosive conditions, these structures can develop into erosional pockets and mat chips. If calm conditions prevail, flip-overs get glued to the mat surface, being overgrown by a newly-developed microbial mat (Fig. 5E).

Commonly, after storm events *microbial mat chips* are spread all over the lower supratidal flat. They are irregularly-shaped, eroded mat fragments, often with rounded edges, flat-planar, and with flexible-cohesive behavior (Fig. 5F). Many of them can be transported away by currents, become glued and overgrown by new mat growth, or they can be completely destroyed.

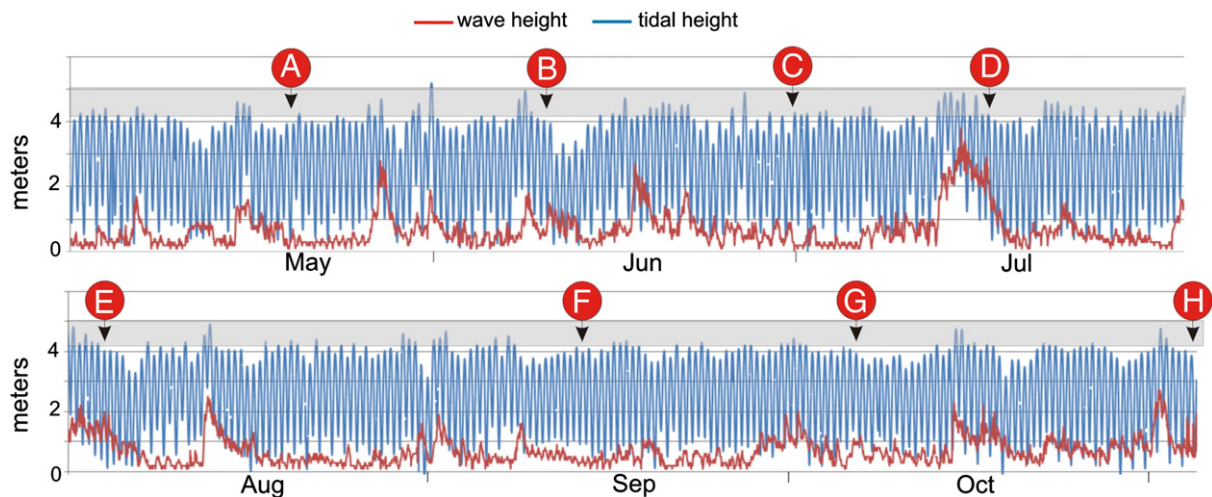


Fig. 3. Tidal and wave heights from May to October, 2010. Inundated supratidal zone is shown by tidal height above 4.1 m in a colored rectangle. The circles identify dates of field sampling.

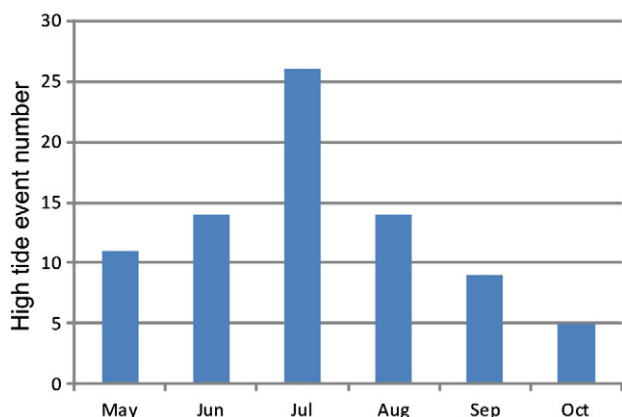


Fig. 4. Monthly frequency of high tide events during which the supratidal area was inundated.

Gas domes are bulges in the mat surface that occur when gases trapped beneath the relatively impermeable microbial film accumulate, increasing the pressure and pushing the mat upward (Noffke et al., 2001) (Fig. 5G). The microbial cover is detached from the underlying substrate producing an upward buckle with a hollow cavern underneath (Fig. 5H). They were typically abundant along the normal high water level especially in June, July and August, when the higher frequency of tides reaching the supratidal zone occurred (Fig. 4). Tides had a dual effect. First, periodic inundation kept the tidal flat surface saturated (helped by lower temperatures during winter) allowing microorganisms to thrive forming a sealing, coherent biofilm or mat (Pan et al., 2013a,b). Secondly, the rising tide pushed upward the gases derived from organic matter decay (Noffke, 2010), whose production by microbial activities was also enhanced by frequent inundation. Gas dome dimensions were mainly 3 to 20 cm in diameter. Each gas dome can last several days and when gas finally escapes they collapse producing a wrinkled surface (“petee” sensu stricto, Eriksson et al., 2007) commonly composed of 3 to 5 folds arranged in a radial or crescent-shaped pattern (Fig. 5I).

On the other hand, *photosynthetic domes* (Bouougri et al., 2007) are small domes formed by deformation of the elastic surface layer due to accumulation of oxygen released as a by-product of cyanobacterial photosynthesis (see arrow in Fig. 5E). Occasionally, they dominate the surface morphology and form the so-called *blistered mat* (Fig. 5I). Under erosive conditions the small bulges were eroded and torn providing an irregular pattern (Fig. 5J).

3.3. Sedimentation on an artificial substrate

Sediment deposition and erosion and biofilm formation over an artificial substrate placed in the supratidal area were followed during several months starting in May 2010 (Fig. 6A). Following twenty-one days lapsed time since placing the tile (Fig. 6B, corresponding to June 9) and after three flooding events in the supratidal area (see Fig. 3), a thin biofilm was formed covering the tile. Typical structures, such as blisters, gas domes, mat chips and flipped-over mats could be observed. In June 28 (19 days lapse time between surveys), after consecutive inundation events during three days twice a day (Fig. 6C), the tile shows the effects of high-energy input into the upper tidal flat with moisture retention. The biofilm was thickening on the tile and some wrinkles were formed probably due to dragging of currents over the biofilm loosely attached to the smooth, flat tile surface. The latter fact reflects the flexible behavior of the biofilm. In July 15 (Fig. 6D, corresponding to 17 days lapse time), after a strong storm event, the microbial biofilm over the tile was mechanically disrupted. In turn, the adjacent tidal flat surface presented gas domes. The sedimentary surface presented a smooth aspect, likely as a result of the deposition of fine-grained sediment by inundation the day prior to the survey. Fig. 6E corresponds to

August 4 when, during the 20-day lapse time, there were two flooding events. A few days prior to this survey, the upper tidal flat was inundated and the increase in wave energy cleaned the tile. However, gas dome remained since the previous sampling event (see upper left side of Fig. 6E); some of them collapsed and the mat-surface had a blister appearance again. After 40 days (Fig. 6F; September 13), three storm events occurred. Microphytobenthos colonized the tile forming a very thin biofilm but the considerable mechanical energy reaching the supratidal zone did not allow it to develop. The tidal flat presented the typical mat cracks formed by shrinkage of the mat-surface under prolonged subaerial exposure, evidence of a drastic drop in the number of flooding tides reaching the supratidal zone (Fig. 4). In October 7 (Fig. 6G, lapse time of 24 days), almost no water reached the supratidal zone and the higher radiation in this period of the year resulted in an intense desiccation of the topmost sediments. Finally, Fig. 6H corresponds to November 2 (26 days lapse time), with two inundation events taking place in the supratidal area during the lapse time. No major changes were observed in the tidal flat, except for an increase in the moisture content of the sediments (the photograph was taken two days after the last of these events).

4. Discussion

Ancient analogs of mesotidal systems are not always easy to identify because they are characterized by complex associations where tidal effects interplay with other hydrodynamic processes (Longhitano et al., 2012). In the study area, the tidal dominance in the main channel of the estuary is reflected by the development of large dunes ($H = 4$ m height). This tidal depositional system is possible due to the mesotidal range (2.5 and 3.4 m during neap and spring tides, respectively) that makes currents sufficiently strong to create those bedforms. On the adjacent margins of tidal channels, the depositional environment is also influenced by tides with wide tidal plains being formed due to sedimentation. These laterally co-existing subenvironments have different preservation potential in the stratigraphic record; tidal channels tend to be among the best preserved whereas the upper intertidal zone is the most poorly preserved (Davis, 2012).

The upper intertidal and the supratidal zones at Puerto Rosales are colonized by microbial mats. Specific habitats are preferred by the microorganisms that form microbial mats. One important component is sediment size, e.g. fine sand composed mainly by quartz grains allows sufficient sunlight penetration in the upper mm for photosynthesis by cyanobacteria (compiled and reviewed by MacIntyre et al., 1996). Another condition is related to the hydrodynamic setting. The formation of microbial mats requires prevailing calm conditions for extended periods of time, in order to allow the dominant filamentous cyanobacteria to migrate between grains and form a filamentous meshwork (Noffke, 2010). Conversely, strong water motion would erode the biofilm or microbial mat. Once formed, they can tolerate high energy events and reworking, but they cannot form under such conditions. The study site is protected by intertidal macrophytes (i.e., the cordgrass *S. alterniflora*) which act as a shield attenuating wave and current energy from the main channel of the estuary. That favors the colonization of the surface sediments by benthic microbial communities, ultimately forming dense microbial mats.

In the supratidal area, periodic flooding during spring tides keeps water supply in balance when the wind direction is not opposite to the flow. Besides, during episodic storm events this zone is also inundated (gray frame in Fig. 3). This means that the microbiota develops during long quiet conditions that usually last up to more than two weeks (the so-called latencies, sensu Noffke, 2010). It is important to bear in mind that not only do these unicellular and filamentous microorganisms have very short generation times (up to 3.2 doublings per day in culture, Admiraal, 1977), but also, while strong currents and sediment disturbance during storms might cause a temporary halt to diatom growth, they would not prevent high doubling rates during periods of

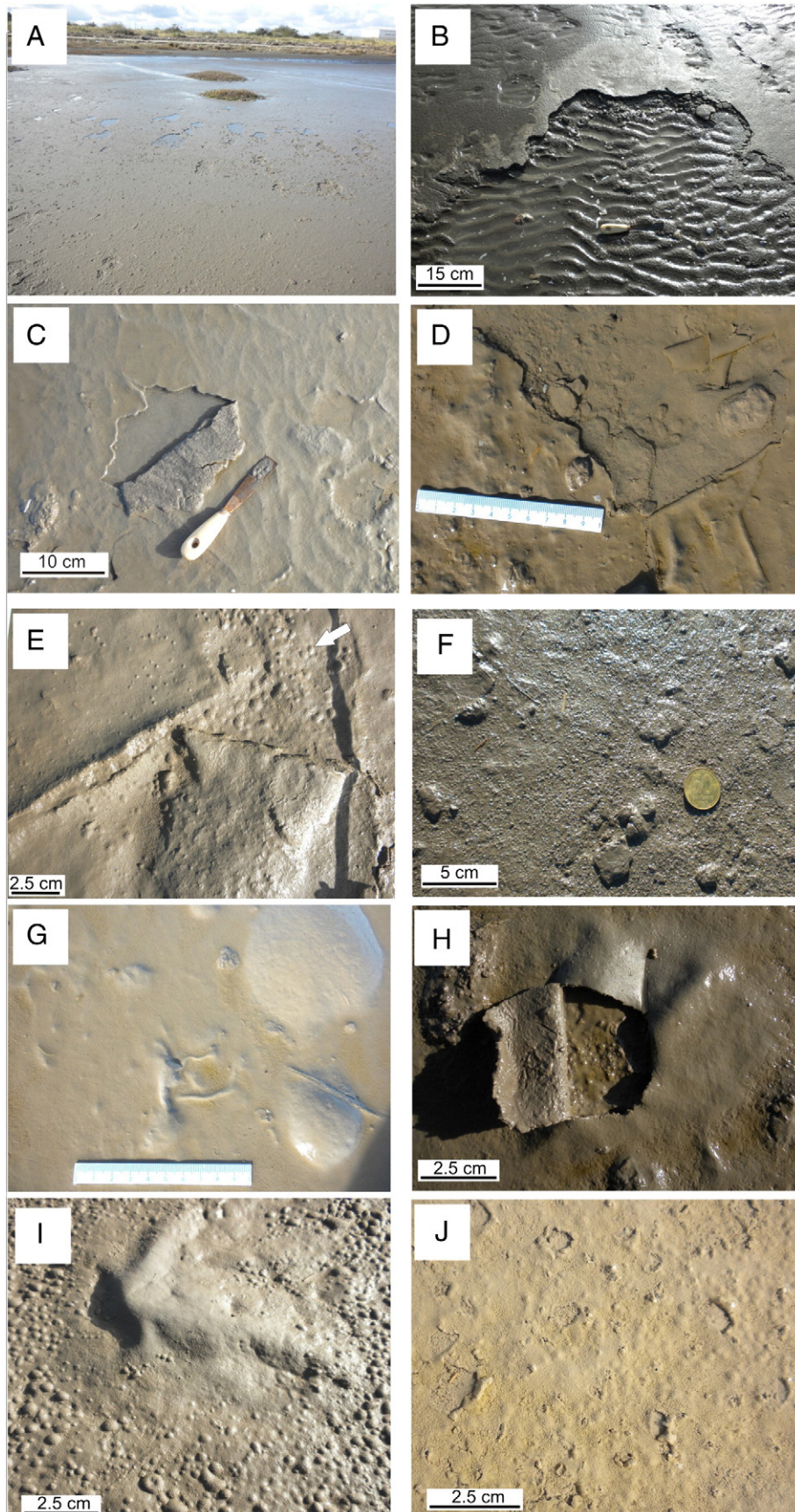


Fig. 5. MISS found after a storm event. (A), (B) Erosional pockets. (C), (D) Flipped-over mats. (E) Detail of the flipped-over mat one month after the original storm event (August). The arrow shows the blister surface developed on the newly-formed biofilm. See the colonized crack (arrow). (F) Microbial mat chips. (G) Gas domes. Note the smooth aspect of the mat due to fine sediment deposition contributing to the leveling of original surface (Noffke, 2010). (H) Cavity underneath a broken gas dome. Note the ripped borders of the mat. (I) Collapsed gas dome after several days of formation. See the formation of surrounding blisters. (J) Broken small bulges by increased energy.

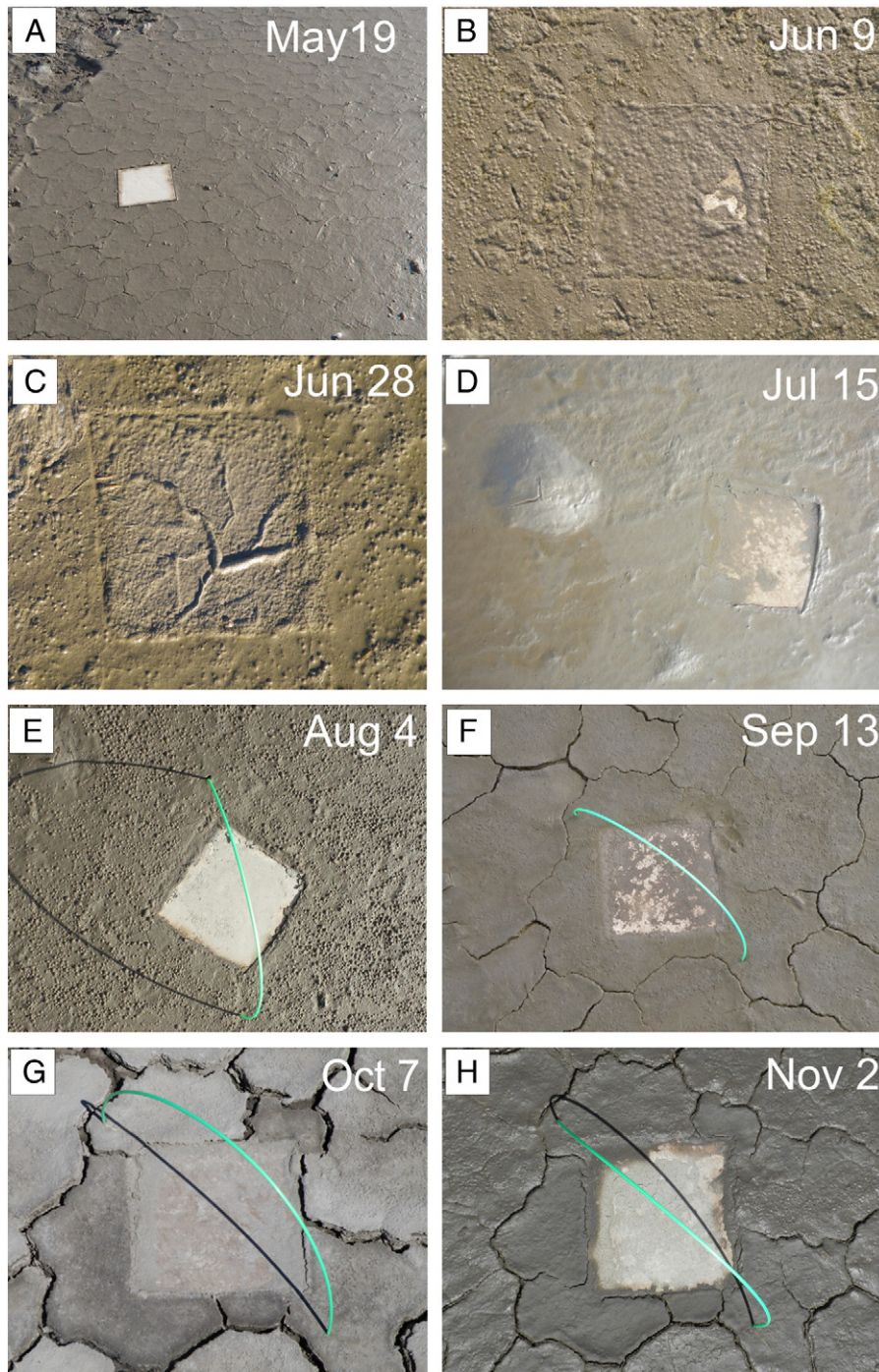


Fig. 6. Colonization sequence of denuded sediments by microorganisms under different energy conditions. See Fig. 3 to identify the hydrodynamics along the sampling. (A) The sediment surface is characterized by polygonal cracks. (B) A thin biofilm is formed after subsequent tidal flat inundations. (C) A thicker biofilm is formed. The crinkles reflect the flexible behavior of the mat over the tile. (D) High energy due to a storm event disrupted the biofilm over the tile. The suspended sediment that remains after the storm is deposited over the flat and consequently the mat is enriched by fine-grain particles. A gas dome was formed. (E) After 20 days lapsed time the gas dome remained and a blister-mat covered the flat. (F) Mat cracks are formed by prolonged subaerial flat exposure. (G) Deep cracks as a consequence of desiccation. The openings expose the underlying sediments. (H) Re-wetting after tidal inundation promotes the re-colonization of clefts by a microbial biofilm (left bottom corner).

calm weather (Admiraal and Peletier, 1980). For instance, the transition from a thin and fragile biofilm to condensed fibrillar meshworks of mat consistency needs several weeks of non-burial (Gerdes and Klenke, 2007). This eventually results in the supratidal zone being colonized by a coherent and planar epibenthic mat, with the filamentous cyanobacteria *M. chthonoplastes* becoming the main mat-builder. This kind of mat effectively biostabilizes the sediment, ultimately resulting in type I biostabilization (Noffke, 2010), which raises the critical velocity

for initial erosion, so the tidal flat is protected from spring tidal currents. Under this condition, it is common to find different MISS in the supratidal zone.

During storms, there is an energy increase in the supratidal zone due to tidal currents and waves (Fig. 3). Noffke (2010) has stated that epibenthic microbial mats can withstand currents of up to 160 cm s^{-1} velocity, even though the microbial mat can be mechanically destroyed or modified by the effect of strong storms (Fig. 5). A consequent

deposition of fine-to-medium grained sand during the slack water period occurs at high tide. When the energy of the environment diminishes, the tidal flat is covered by smaller-size particles (Figs. 6D, 7). After cessation of the hydraulic reworking, the microorganisms colonize the sediments forming a biofilm (Fig. 6B) which firstly matures into an epibenthic microbial mat (Fig. 6C) and then a thicker microbial mat begins to form (Fig. 6F). Under periodic inundation during spring tides, silt in suspension settles down by baffling (Fig. 7) due to the vertical orientation of filamentous cyanobacteria (Noffke, 2010). The mat is enriched by silt-sized particles and also grows due to the secretion of exo-polymeric substances (EPS), particularly important in the supratidal zone due to the presence of *M. chthonoplastes*.

Although Eriksson et al. (2010) considered the MISS as diagnostic of clastic flats lacking storm influence, we found that some of these structures were capable of withstanding high energy conditions. The biostabilization effect of microbial mats prevents erosion, and several MISS reflect the wave action exerted during high spring tides (Fig. 5). In turn, these structures evidence an interaction between physical-hydraulic processes (i.e. a result of the interplay between tides and storms) and microbial mats, that may be used to infer the relative energy of a depositional environment in the sedimentary record (Davis, 2012).

In vertical cross-sections of tidal flat sediments, a microsequence can be identified, with the largest grains lying in the underlying horizons and grain size decreasing toward the topmost horizons, capped by microbial mat (Noffke et al., 1997). Noffke (2010) defines such microsequences as the result of microbial interaction with changing sediment dynamics. Each microbial mat represents a period of non- or low-rate deposition (which can include several spring tide events), and this lamination represents the biostabilization against erosion. Each discrete layer of the microsequence denotes a depositional event as a consequence of a storm, and the grain size and thickness of the deposit would be correlated to the energy level (Fig. 8). During the development of the microbial mat, sand grains transported by wind from the upper zones of the supratidal area can be trapped and glued in the mat surface by EPS. Then the sediments are bounded by EPS and incorporated into the mat as it grows upward (*binding*, sensu Noffke and Krumbein, 1999), and recognized as “floating” grains in the microsequence. These grains are usually oriented with their long

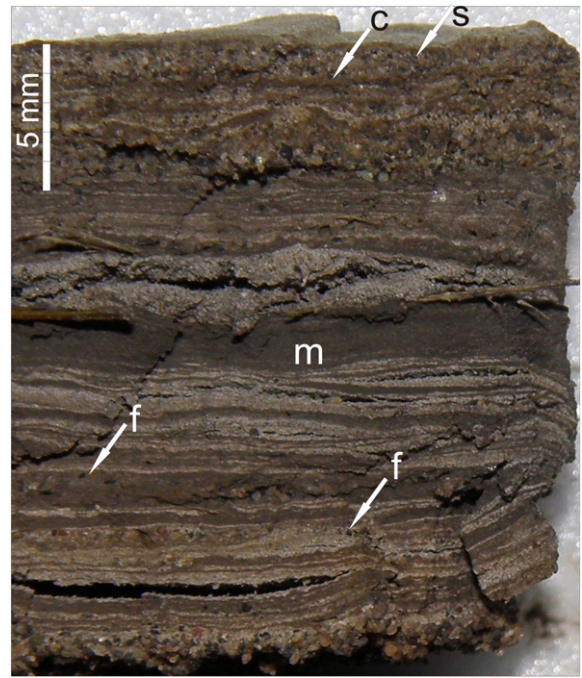


Fig. 8. Tidal flat sediment core obtained July 15, 2010, after a storm event, showing the characteristic biolaminites of microbial mats formed in the supratidal area. The dark layers are microbial mats (m) corresponding to calm conditions, with interspersed “floating” grains (f). The upper 1 mm is mainly formed by sand (s) and corresponds to the storm that occurred on July 10, 2010. This layer evidences an increase in the energy, lying over a thin microbial mat that indicates calm conditions (c).

axes parallel to the bedding plane (Noffke et al., 1997). In siliciclastic peritidal systems without precipitation of carbonate, deposition of silt and sand is the most important process to preserve mat-related structures (Eriksson et al., 2010). In comparison, tidal rhythmites, sequences of sediments that are produced by cyclic conditions, are typically associated with intertidal flats at the border of estuarine or marine settings in general, although there is a progressive truncation of rhythmite cycles across and up the intertidal flat because of its slope (Archer, 1998).

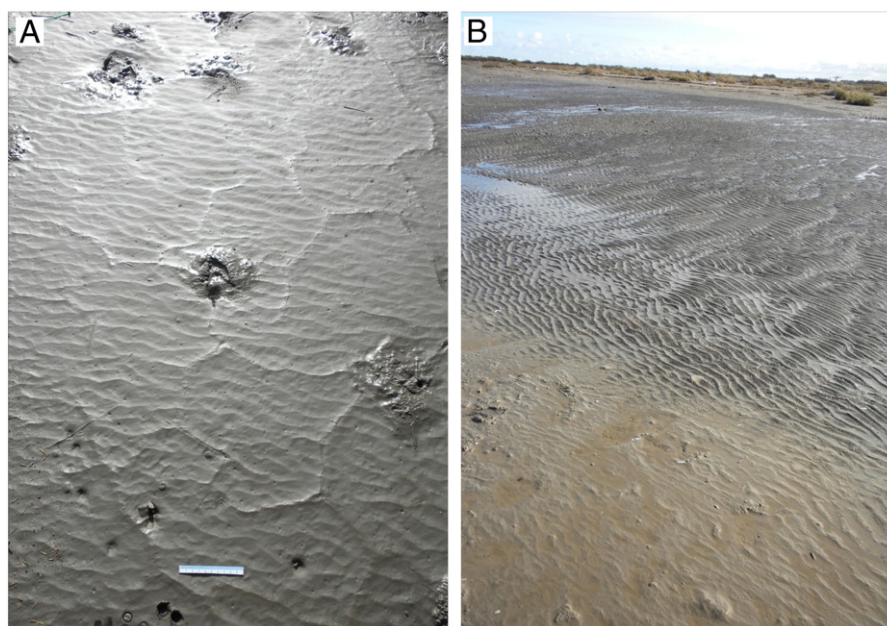


Fig. 7. Appearance of the supratidal flat after a storm. A thin layer of very fine sediment covers the underlying bedforms. (A) Note the incipient, recently colonized polygonal cracks. (B) Note the boundary of the fine sediment deposition in the bottom-left side of the photograph.

Unlike rhythmites, which represent several and consecutive tidal cycles, the microsequences and MISS discussed here were formed under particular tidal conditions such as storms.

5. Conclusions

In most shallow marine depositional systems, high energy conditions created during storm events mask or rework any evidence of tidal activity, making it difficult to recognize in the rock record. However, the presence of microbial mats biostabilizes the surface sediments acting against erosion, enhancing the preservation potential of such high-energy events. The results presented here, can be considered as signatures of sporadic tidal influence during strong storm events in the supratidal zone.

Moreover, the characteristic bedding on the study site shows microsequences of sediments decreasing in size toward the topmost layers capped by microbial mats that reflect calm conditions. The largest grain sizes evidence the high-energy storm events during which the water reaches the supratidal zone. In contrast to *rhythmites* that comprise consecutive tidal cycles, the recognized microsequences reflect fluctuation in current energy, evidencing storm events.

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