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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.

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 ~1.3 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 m, and L >100 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°55′30″ S; 62°03′00″ 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).

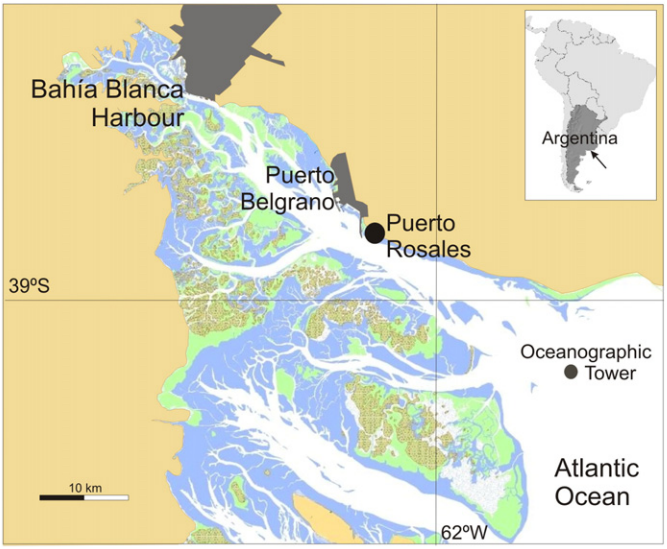

Fig. 1. Location of the study area within the Bahía Blanca Estuary, SW Atlantic Ocean.

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 × 15 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 m when wind velocity was <40 km h^{-1}. On the contrary, when the NNW wind reached velocities >40 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 km h^{-1}, waves reached more than 2 m height (yellow column in Fig. 2). Similar results were achieved under strong winds (>40 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 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