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Deformed microbial mat structures in a semiarid temperate coastal setting

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ABSTRACT

This study focuses on sedimentary structures formed by microbial consortia, in a particular coastal setting, an ancient tidal channel, separated from the ocean by a sandy spit and connected by a blind tidal channel at the opposite end. Most studies in modern and ancient environments consider water movement as the triggering mechanism acting in the formation and deformation of sedimentary structures. As such, the paper documents the presence of several microbial structures such as shrinkage cracks, flip-over mats, microbial chips, and multidirectional ripples which are related to tidal processes, while bulges and gas domes structures are formed after occasional inundation events. However, the more conspicuous structures covering a great area at the study site are folds and roll-ups, the product of deformation of microbially induced structures by the action of sporadic spring-tidal currents due to strong winds. Therefore, the objective of this research is to document modern sedimentary structures in a coastal area and to provide a mechanistic explanation for their formation, based on the interplaying effects of the moisture variation and high shear stress. Also, several microbial sedimentary structures are distinguished throughout vertical sediment cores, such as microbial chips, detached mat, sponge fabrics, tears, and concentric structures, which are identified in a sedimentary profile. Through the recognition and interpretation of modern sedimentary deformation structures, this study contributes empirical tools for the reconstruction of analogous paleoenvironments in fossil studies.

1. Introduction

Microbial mats consist of consortia of prokaryotic and eukaryotic microorganisms that colonize the uppermost sediments in coastal environments altering sedimentary processes and their physicochemical properties. Thus, they have been termed a biogeomorphological force in sediments (Stal, 2010). There are two important keystones that need to be emphasized regarding the process of sediment colonization by microorganism: cohesion and geochemical variations. For cohesion, the biostabilization (*sensu* Paterson, 1994) is achieved mostly through the presence of filamentous cyanobacteria and benthic mobile diatoms in the sedimentary surface. The first ones entangle particles, and most of the motile benthic microorganisms present in the surface are embedded in highly adhesive mucilages, collectively known as EPS (extracellular polymeric substances, Decho, 1990). Consequently, the characteristics of sediments are altered, thus increasing the erosive critical threshold in aquatic environments under unidirectional currents (Hagadorn and McDowell, 2012); tidal currents (Noffke, 2010), and even wave-shear stress (Cuadrado et al., 2014).

On the other hand, the various metabolic activities of microbes alter the local geochemical and physicochemical conditions of sedimentary systems (Glunk et al., 2011), so microbial mats promote the precipitation or dissolution of some minerals. As the microbial mat has a high percent of organic matter which is rarely preserved in the fossil record, the associated mineralization provides the required lithification for preservation of microbial structures and activities. An indirect evidence of an original presence of microbial mats are the microbially induced sedimentary structures (i.e., MISS after Noffke et al., 2001a), which can be recognized in the sedimentary record. In that sense, Schieber (2004) has classified different features found in sandstones and mudstones considering steps ranging from the mat growth to the final stages of diagenesis with the destruction of organic matter and mineral precipitation. This author included the formation of polygonal cracks, roll-up, and flip-over structures within the processes involving physical mat destruction in sandstones.

The recognition of microbial mats in modern environments has gathered special relevance in recent years with regards to the

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interpretation of the processes involved in the formation of sedimentary mat structures. Accordingly, recent studies carried out on the Southern Hemisphere since a few years ago (Cuadrado et al., 2012, 2013; Pan et al., 2013a) have recognized typical structures in an estuarine environment in Argentina, where tidal processes are the most important. Similarly, in modern coastal sabkhas, many studies identified sedimentary structures induced by microbial mats being related to marine processes (Gerdes et al., 2000a,b, 2008; Noffke, 2010; Aref et al., 2014 among others), and several studies recognized similar structures in the rock record (Schieber, 1999; Eriksson et al., 2000; Noffke and Awramik, 2013) and also their similarity with analogs of Martian rocks (Barbieri et al., 2006; Stivaletta et al., 2009; Noffke and Awramik, 2013).

Most works in both modern and ancient environments consider water movement as the triggering mechanisms for the deformation of sedimentary mat structures. However, the recognition of the precise physical processes behind fossil mat structures still remains a challenge, since a number of physical processes such as those dominated by currents and wind may produce similar signatures in rocks. For example, a recent study on a coastal sabkha tidal flat carried out in Tunisia (Bouougri and Porada, 2012) introduced the role of strong winds as the main process yielding mat deformation structures. The present research documents deformed sedimentary mat structures in a coastal area that seldom gets flooded by seawater inundation, and where strong winds also prevail. We also identify microbial structures in a vertical sedimentary profile in an attempt to contribute tools for the interpretation of microbial signatures in siliciclastic rocks and their associated processes of formation. This study in a modern setting promotes the recognition of analogous structures in fossil records and the consequent inference in paleoenvironmental research.

2. Methods and study area

This paper is based on *in situ* observation, and field and laboratory studies corresponding to six campaigns carried out in the temperate coastal flood plain environment at Paso Seco, Argentina (40°33′S; 62°14′W, Fig. 1). These campaigns took place in January 2013 (mid Austral summer), October 2013 (mid Austral spring), March 2014 (early Austral autumn), October 2014, December 2014 (late Austral spring), and April 2015. The campaign carried out in March 2014 was performed 1 day after a heavy rainfall, and the one in April 2015 took place coinciding with extraordinary spring tides augmented by strong winds.

The tidal amplitude was measured at spring tide with two HOBO water level loggers (model U20) to identify the tidal mitigation along the tidal channel. The conductivity and temperature of water were measured in the field with a Hanna HI9033 conductivity probe. Cylindrical sediment cores (inner diameter = 8.5 cm; height = 20 cm) were taken from the flats colonized by microbial mats and were cut longitudinally to identify microbially induced sedimentary structures. Sand samples were observed under a Nikon SMZ 1500 optical microscope to determine the mineralogical composition, and the grain sediment distribution was determined by standard sieving techniques.

Microbial consortia were studied from three methodological perspectives: traditional microscopic analysis, scanning electron microscopy (SEM; model JEOL35 CF 8), and community fingerprinting through molecular biology techniques. Accordingly, sampling was consistently done during daytime hours and a discrete number of microbial mat and surface sediment samples were taken for quali-quantitative light microscopy, SEM, and denaturing gradient gel electrophoresis (DGGE) analyses.

The study area, Paso Seco, is located in northern Patagonia (South America, Argentina) (Fig. 1). According to the climatic classification of Argentina proposed by Iglesias (1981), Paso Seco is located within the subdivision called "semiarid temperate of the Meseta" (see Fig. 4 and 5 in Tonni et al., 1999). This climate has an average annual rainfall < 300 mm and the potential evapotranspiration commonly exceeds precipitation (Ferrelli et al., 2012). In spite of its mid latitude and temperate condition, aridity is strong enough in the study area to limit vegetation development (see Fig. 2 in Clapperton, 1993), allowing the formation of a saline system similar to those on the coasts of northern Africa, the Arabian Peninsula, and western Asia (see Fig. 1 in Yechieli and Wood, 2002), and also similar sedimentary structures. Differences between summer and winter are relatively moderate, rather than extreme hot or cold, due to the proximity of the SW Atlantic Ocean. Rainfall is characterized by the large space–time variation, typically of semiarid regions. An important factor to take into account is the prevailing and strong winds from NE quadrant, averaging 35–38 km h^{-1} with frequent gusts up to 100 km h^{-1} (Beigt et al., 2011).

Geomorphologically, the study area comprises a large closed basin (about 2.5 × 0.3 km) colonized by microbial mats, located at a distance exceeding 1.8 km from the coastline of the SW Atlantic Ocean (Fig. 1). Previous studies have stated that this area constituted the remnants of an ancient tidal channel, which was choked by a sand spit that interrupted the outflow of the channel some 100 years ago (Espinosa and Isla, 2011). However, our records during a recent campaign showed that the area is seldom flooded during particular occasions, i.e., when very strong winds combine with the effect of the spring tide to push the seawater through a ridge-runnel channel in the sand spit to enter the water into the basin.

The blind tidal channel, that is located on the W-SW extreme of the study area, initiates in the San Blas channel at the N (Fig. 1b). The tidal amplitude was measured at two points in this tidal channel during a spring tide with HOBO water level loggers, in the mid-section of the total length and at the end of the channel (Fig. 2). While the tidal range was 1.20 m in the mid-section of the channel, it was 0.27 m at the end. Thus, such attenuation on the tide leads to a microtidal classification for the western extreme of study area inundating only tens of meters over the tidal flat (Fig. 3a). The water of the tidal channel has a

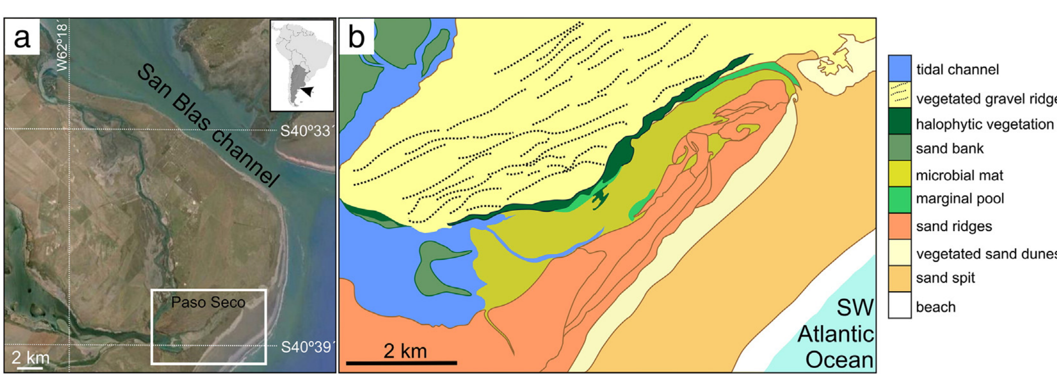

Fig. 1. Study area. (a) Location of the study area in southern Buenos Aires province, Argentina. The inset shows the location of the geomorphologic map. (b) Geomorphologic map showing the coastal plain separated from the sea by a sand spit and connected by a tidal channel to the E.