Geomorphology 276 (2017) 104–115

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Limestone biopitting in coastal settings: A spatial, morphometric, SEM and molecular microbiology sequencing study in the Mallorca rocky coast (Balearic Islands, Western Mediterranean)

F. Pomar [a,*], L. Gómez-Pujol [b], J.J. Fornós [a], L. Del Valle [a], B. Nogales [c,d]

[a] Earth Sciences Research Group, University of the Balearic Islands, Cra. Valldemossa km 7.5, 07122 Palma, Balearic Islands, Spain
[b] SOCIB, Balearic Islands Coastal Observing and Forecasting System (MINECO-CAIB), Parc Bit, Cra. Valldemossa km 7.4, 07121 Palma, Illes Balears, Spain
[c] Department of Biology, University of the Balearic Islands, Crta. Valldemossa km 7,5, 07122 Palma, Balearic Islands, Spain
[d] IMEDEA (CSIC-UIB), Esporles, Mallorca, Illes Balears, Spain

ARTICLE INFO

Article history:
Received 9 November 2013
Received in revised form 6 October 2016
Accepted 9 October 2016
Available online 11 October 2016

Keywords:
Bioerosion
Limestone rock decay
Biopits
Rivularia sp.
Rocky coast
Mallorca

ABSTRACT

Biological agency on rock coasts has been widely recognised over recent decades. This study deals with the distribution and morphometric characteristics of microforms features developed by cyanobacteria (*Rivularia* sp.) on coastal limestone outcrops. These coastal microforms, known as biopits, have a small rounded basin shape a few millimetres in size. Environmental and geological data were collected from 100 random rock surface spots from Punta des Faralló cape (Mallorca, Western Mediterranean), from which major controls on the spatial distribution of biopits were established. Additionally, morphological data on 382 biopits determined the diagnostic morphometry of these features and their enlargement mechanisms. The results indicated that biopits exhibit a preferential location in shaded exposures and sheltered areas from prevailing winds and waves, avoiding direct insolation and desiccation. Other major controls on these microforms location and development were variables such as the rock surface slope and the distance to the coast (i.e. influence of splash and spray). Shadow spots displayed higher biopits density than other locations according to the patterns determined by environmental and geomorphological factors at the study site. Morphometric analyses showed that biopits have a width twice their depth. The average width of the microforms was 6.49 ± 2.40 mm and the average depth 2.46 ± 1.09 mm. Most frequently, the width/depth ratio was 2 or larger. This characteristic shape ratio was an additional factor that plays a role in maintaining the necessary humidity for microorganisms associated with biopits.

1. Introduction

Rock coasts are non-linear dynamic systems dominated mainly, but not only, by erosional forms where biotic and abiotic processes denude the landscape (Naylor and Stephenson, 2010). During the last few decades, rock coast researchers have sought to determine which processes are dominant in shaping rock coasts as well as the related erosion rates (Trenhaile, 2002; Naylor et al., 2010; Naylor et al., 2014). Researchers have largely focused their efforts on rock resistance, lithological and geological structure control (i.e. Dickson, 2006; Cruslock et al., 2010; Stephenson and Naylor, 2011a, 2011b), inheritance (Trenhaile et al., 1999; Gómez-Pujol et al., 2006a) or the balance between rock decay and wave erosion (Stephenson and Kirk, 2000a, 2000b and Gómez-Pujol et al., 2006b). At this point it is interesting to note that, at large and meso-scale landforms, different erosion mechanisms produce similar landform features or products in similar lithologies, whereas very often different meso-scale features and shore platforms result from lithologically similar rocks (Cruslock et al., 2010). However, especially at meso- and micro-scale landforms, a large suite of biogeomorphic processes operate in rock coasts and the biological agency on rock coasts is widely recognised (Spencer, 1988; Naylor et al., 2002; Naylor and Viles, 2002; Spencer and Viles, 2002; Naylor, 2005; Fornós et al., 2006a, 2006b; Stephenson and Naylor, 2010; Coombes et al., 2011; Moses, 2013; Coombes, 2014; Furlani et al., 2014). Much of this research suggests that the main erosive vector in rocky coasts is the presence of macroorganisms and microorganisms whose biological activity erodes, weakens or contributes to the rock fatigue and prepares rock surfaces for subsequent geomorphic processes (Naylor et al., 2012).

Very diverse, evolutionarily divergent sets of organisms engage in the rock coast biogeomorphic processes, including bacteria, algae and animals (Schneider, 1976; Schneider and Torunski, 1983; Spencer, 1988; Coombes, 2014). Between them, microorganisms or microbial biofilms are a common feature on natural rock outcrops and particular attention has been focused on their role as agents of geomorphological change on rock surfaces, especially on carbonate rocks (Jones, 2000;

* Corresponding author.
E-mail address: xisco.pomar@uib.cat (F. Pomar).

http://dx.doi.org/10.1016/j.geomorph.2016.10.014
0169-555X/

Naylor and Viles, 2002; Fornós et al., 2006a, 2006b; Gorbushina, 2007; Viles et al., 2008; McIlroy de la Rosa et al., 2012b; Cutler et al., 2015).

Microorganisms have several strategies to colonise and live on and in the rock (Pohl and Schneider, 2002; Hoppert et al., 2004; Viles et al., 2008; Viles, 2012) resulting in biogeomorphological activity, which includes processes such as bioerosion, bioconstruction or bioprotection (Naylor and Viles, 2002; Coombes, 2014). These processes and their spatial extent are determined by environmental and ecological conditions (Spencer and Viles, 2002; Cutler et al., 2013; Coombes et al., 2015). Zonation is typical on rocky shores, since organisms respond differently to the effects of waves, impacted by the spatial extent of splash and/or spray (Palmer et al., 2003), insolation (Coombes and Naylor, 2012), wind, temperature fluctuations, changes in seawater chemistry, and tidal inundation hydroperiod (e.g. Mills et al., 2013). Additionally, this zonation is controlled by biological/ecological factors such as competition for food, space, sunlight, predation, or trophic relations (Torunski, 1979; Fornós et al., 2006a, 2006b; Vidal et al., 2013).

Cyanobacteria, fungi and lichen are the typical epilithic and endolithic communities of microorganisms that decompose carbonate rock (Danin, 1983; Danin and Garty, 1983; Gorbushina and Krumbein, 2000; Pohl and Schneider, 2002). Among them, cyanobacteria are the most characteristic communities related to limestone coastal rock decay processes (Golubic et al., 2000; Chacon et al., 2006; Garcia-Pichel, 2006). They bore the rock, developing a dense network of galleries and boreholes less than a few microns in the outer 1 mm of the rock surface (Torunski, 1979; Viles and Moses, 1998; Golubic et al., 2000; Viles, 2001; Chacon et al., 2006; Gorbushina, 2007; McIlroy de la Rosa et al., 2012b; Naylor et al., 2012). This behaviour is due to the need of cyanobacteria to find an equilibrium depth where sun and humidity factors are balanced. Therefore, this results in a density of boreholes that give a porous texture to the rock surface increasing the effectiveness of rock decay agents and erosion processes, as well as in the development of dissolution forms (Naylor and Viles, 2002). In limestone rocks this activity induces nanoscale and microscale weathering morphologies called *biopits*, *weathering pits* or *alveoli* (Moses and Smith, 1994; Viles, 2001; McIlroy de la Rosa et al., 2012a, 2012b; Naylor et al., 2012). Microscale morphologies, such as biopits are frequently reported associated with certain endolithic species associated to the production of well-rounded pits (c. 0.2 to 1.5 mm in diameter) and deeply incised in their substratum (Gehrmann et al., 1992; Danin, 1983; Gómez-Pujol and Fornós, 2001; Ford and Williams, 2007; Gómez-Pujol and Fornós, 2009). Nevertheless there is a lack of commonality in terminology and some discrepancies exist within literature related to the spatial scale of analysis and the associated features referred as biopits (McIlroy de la Rosa et al., 2012b). Throughout this paper and in following other researchers (e.g. Viles, 1995) the term 'biopit' is used to describe this microscale feature ranging from 0.2 to 1.5 mm in diameter.

Despite the frequencies of biopit occurrence on coastal limestone (Lundberg, 2009; Gómez-Pujol and Fornós, 2009) many gaps exist in our understanding on the mechanisms by which microorganisms contribute to biopit formation and the environmental controls that explain their spatial variability. Moreover, the impact of the environmental factors on a rocky coast may be conditioned by structural features of the area (Cruslock et al., 2010). Against this background, our study encompasses biopits spatial distribution assessment, morphometry studies, Scanning Electron Microscopy (SEM) observations and taxonomic determination using molecular techniques in order to unravel how environmental and geological features mediate the microorganisms distribution and the resulting biopits development and sequential enlargement.

2. Study area

Located in the north-eastern coast of Mallorca (Western Mediterranean) Punta des Faralló (Fig. 1) constitutes an elongated cape of approximately 1.2 km^2. This location was selected because biopits are well developed –as well as other coastal karren features – and have shown spatial variability in its development (Gómez-Pujol and Fornós, 2009). Additionally rock properties (i.e. rock texture, join density and porosity) are quite homogenous (Balaguer, 2005; Fornós et al., 2006a, 2006b) and its rugged nature offers a natural laboratory to investigate the role of different agents, controls and processes in microscale rock coast features shaping.

Punta des Faralló is characterised by temperate Mediterranean climatic conditions with a mean annual temperature of 19.4 °C and mean annual precipitation of 616 mm. Prevailing wind directions are NNW and SE and seasonal changes are obvious with a strong southern component during summer and autumn and a northern component in winter (Cañellas et al., 2007).

Prevailing and largest waves at the study site proceed mainly from the north. Almost 30% of the waves come from this direction and reach significant wave height between 0.2 m and 2 m (Cañellas et al., 2007). Waves from the east, northeast, and southeast directions constitute 12% of waves below 1 m height. Tides are negligible in the Western Mediterranean. The tidal range is < 0.25 m, nevertheless combined tides and atmospheric pressure can cause sea level rise by nearly 1 m above mean sea level (Basterretxea et al., 2004).

Geologically Punta des Faralló is composed of Cretaceous folded calcarenites formed by bioclastic carbonate with an incipient dolomitisation. The rock has a low intraparticular porosity of about 1.29% with a density of 2.35 g/cm^3. The mineralogical composition of the rock is 91.4% calcite and 8.6% quartz. The rock has a vertical bedding and horizontal schistosity (Fornós et al., 2006a, 2006b).

From a geomorphological point of view, Punta des Faralló protrudes NNE-SSW as an elongated rocky cape of about 150 m in length and 80 m in width. On the east coast, macroscale examples include a 16 m-high vertical cliff that rests on a 5 m wide shore platform with abundant microscale features, such as basin pools and crevices. The cliff height decreases to the south. From the top of the cliff the topography shows a smooth slope decreasing in height towards the western coast. The west coast steepens gently and has a continuous notch and trottoir rims. Finally, superimposed upon these macroscale and mesoscale features there are micromorphologies such as rillenkarren or biopits, the last of which constitute the focus of this paper.

3. Data and methods

The study approach integrated field observations and laboratory methods (Fig. 2). Field observations dealt with the spatial presence of biopits and the related physiographical and environmental constraints, as well as the morphometric characterisation on the microscale features. Geospatial statistical analyses determined the main constrains of the distribution of these microforms. Additionally, laboratory methods tried to identify what group of microorganisms were the responsible for the formation of biopits and to explore through the use of SEM images the way they contribute to rock decays and to the biopit formation and enlargement.

3.1. Field methods

3.1.1. Sample location and description

In order to assess the potential variation in biopits presence or absence, we examined 100 locations (throughout the paper rock surface spots) along two parallel transects, separated by about 20 m, crossing the cape from N-NE to S-SW. From a northward arbitrary starting point, a rock surface spot was selected randomly every 10 m and georeferenced using a GARMIN GPSMAP 76CSx GPS (Fig. 3A). At each spot the sampling strategy consisted in obtaining different attributes from a 20 × 20 cm frame surface (Fig. 3B). This frame size was previously used at this study site by Fornós et al. (2006a, 2006b)) in order to characterise rock properties and ecological description of coastal rock grazing organism communities. The attributes we obtained from each spot site