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The influence of light attenuation on the biogeomorphology of a marine karst cave: A case study of Puerto Princesa Underground River, Palawan, the Philippines

Martin A. Coombes [a,*], Emanuela C. La Marca [a], Larissa A. Naylor [b], Leonardo Piccini [c], Jo De Waele [d], Francesco Sauro [d]

[a] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY
[b] School of Geographical and Earth Sciences, University of Glasgow, UK
[c] Department of Earth Science, University of Firenze, Italy
[d] Department of Biological, Geological and Environmental Sciences, University of Bologna, Italy

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ABSTRACT

Karst caves are unique biogeomorphological systems. Cave walls offer habitat for microorganisms which in-turn have a geomorphological role via their involvement in rock weathering, erosion and mineralisation. The attenuation of light with distance into caves is known to affect ecology, but the implications of this for biogeomorphological processes and forms have seldom been examined. Here we describe a semi-quantitative microscopy study comparing the extent, structure, and thickness of biocover and depth of endolithic penetration for samples of rock from the Puerto Princesa Underground River system in Palawan, the Philippines, which is a natural UNESCO World Heritage Site.

Organic growth at the entrance of the cave was abundant (100% occurrence) and complex, dominated by phototrophic organisms (green microalgae, diatoms, cyanobacteria, mosses and lichens). Thickness of this layer was 0.28 ± 0.18 mm with active endolith penetration into the limestone (mean depth $= 0.13 \pm 0.03$ mm). In contrast, phototrophs were rare 50 m into the cave and biofilm cover was significantly thinner (0.01 ± 0.01 mm, $p < 0.000$) and spatially patchy (33% occurrence). Endolithic penetration here was also shallower (<0.01 mm, $p < 0.000$) and non-uniform. Biofilm was found 250 m into the cave, but with a complete absence of phototrophs and no evidence of endolithic bioerosion.

We attribute these findings to light-induced stress gradients, showing that the influence of light on phototroph abundance has knock-on consequences for the development of limestone morphological features. In marine caves this includes notches, which were most well-developed at the sheltered cave entrance of our study site, and for which variability in formation rates between locations is currently poorly understood.

1. Introduction

Caves provide a unique habitat for rock-dwelling microorganisms that in turn are thought to have a geomorphological role via their involvement in weathering, erosion and mineralisation (Barton, 2006; Barton and Jurado, 2007; Riquelme and Northup, 2013). Cave characteristics such as dimension, morphology, location, orientation and lithology have an important influence on the structure of the biological communities found in these environments (Lamprinou et al., 2012). This appears to be especially important for limestone caves, where biogeomorphological interactions between rock and biota are strongest (e.g., Cañveras et al., 2001; Jones, 2010; Pasic et al., 2010).

The ecology of cave walls (including marine caves) is characterised by a decrease in biomass towards the interior, resulting from the presence of marked environmental gradients, including light, oxygen, temperature and nutrient availability. Light attenuation is particularly critical for phototrophs (Gili et al., 1986). In terrestrial caves in Spain, for example, Roldàn and Hernandez-Mariné (2009) found that biofilms comprised of cyanobacteria, green microalgae, diatoms, mosses and lichens on the walls and floors were thinner farther from the entrance, and had lower species diversity. Similarly, Cuezva et al. (2009) found that microbial colonies on rock surfaces are concentrated at the entrance of Altamira Cave, Spain, and that these microorganisms are involved in biomineralisation and $CaCO_3$ deposition. While the influence of light attenuation on cave microbial communities is clear, there has been very little attempt to relate these patterns to biogeomorphological processes. This is an important research gap because the relative contribution of biological processes (i.e., bioweathering, bioerosion and bioprotection) to the formation of

* Corresponding author.
E-mail address: martin.coombes@ouce.ox.ac.uk (M.A. Coombes).

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distinct morphological features associated with cave systems is relatively poorly understood compared to open coast rocky shores (e.g., Coombes 2014). For marine caves this includes notches, which are very common and well developed on Mediterranean and tropical limestone coasts (e.g., Trudgill, 1976; De Waele et al., 2009; Furlani et al., 2011; Moses, 2013; Pirazzoli and Evelpidou, 2013).

The mechanisms involved in notch formation have been debated (Furlani et al., 2011), but probably involve a combination of chemical, biochemical, biomechanical and physical processes (i.e., waves) (see De Waele and Furlani, 2013, and references therein). Some researchers suggest that bioerosion is the key process controlling the rate of marine notch formation (e.g., Evelpidou et al., 2012; Pirazzoli and Evelpidou, 2013; Boulton and Stewart, in press), yet direct quantitative evidence of bioerosion is scarce (but see Furlani and Cucchi, 2013).

Here we describe a study aimed at addressing this knowledge gap using the Puerto Princesa Underground River cave system, the Philippines, as a case study. The study had three main aims: (1) to examine the presence and characteristics of ecology (focusing on microorganisms) on cave walls in relation to distance from the entrance and therefore availability of light; (2) to determine the biogeomorphological significance of these organisms in a context of bioweathering and bioerosion, and thereby; (3) contribute to understanding of biogeomorphological processes in the development of marine cave morphological features, including notches.

2. Study site

Palawan is located between 11°50′ and 12°20′ latitude north, and 117°00′ and 120°20′ longitude east, in the south-western part of the Philippines archipelago. Climate is characterised by a dry season (November to May) and a wet season (June to October), with stable temperatures throughout the year ranging from about 26 °C to 28 °C (Piccini and Iandelli, 2011). The island is narrow and elongated, mostly mountainous, and divided into three geologic sectors by two north–south oriented tectonic depressions. The Saint Paul Dome karst ridge divides the northern from the central sector, located east of Ulugan Bay about 50 km northeast of Puerto Princesa (Fig. 1). The ridge covers an area of about 35 km^2 (10 km long and roughly 4 km wide) and is formed of massive to roughly bedded (400 m thick) light to dark grey Oligocene–Miocene limestone rich in fossils (Hashimoto, 1973). The site is a National Park and an UNESCO natural World Heritage Site. Structurally the area consists of a multiple northwest dipping homoclinal relief, limited by northeast–southwest oriented faults that control the general morphology of the karst landscape, including the orientation of dolines and the development of major caves.

One such cave system is the Puerto Princesa Underground River (PPUR) complex, a 32 km long cave that consists of an active branch developing at the present sea-level, and two relict levels of huge tunnels and large breakdown chambers at approximately 5–10 and 60–80 m above present sea level. The cave has had a long and multiphase

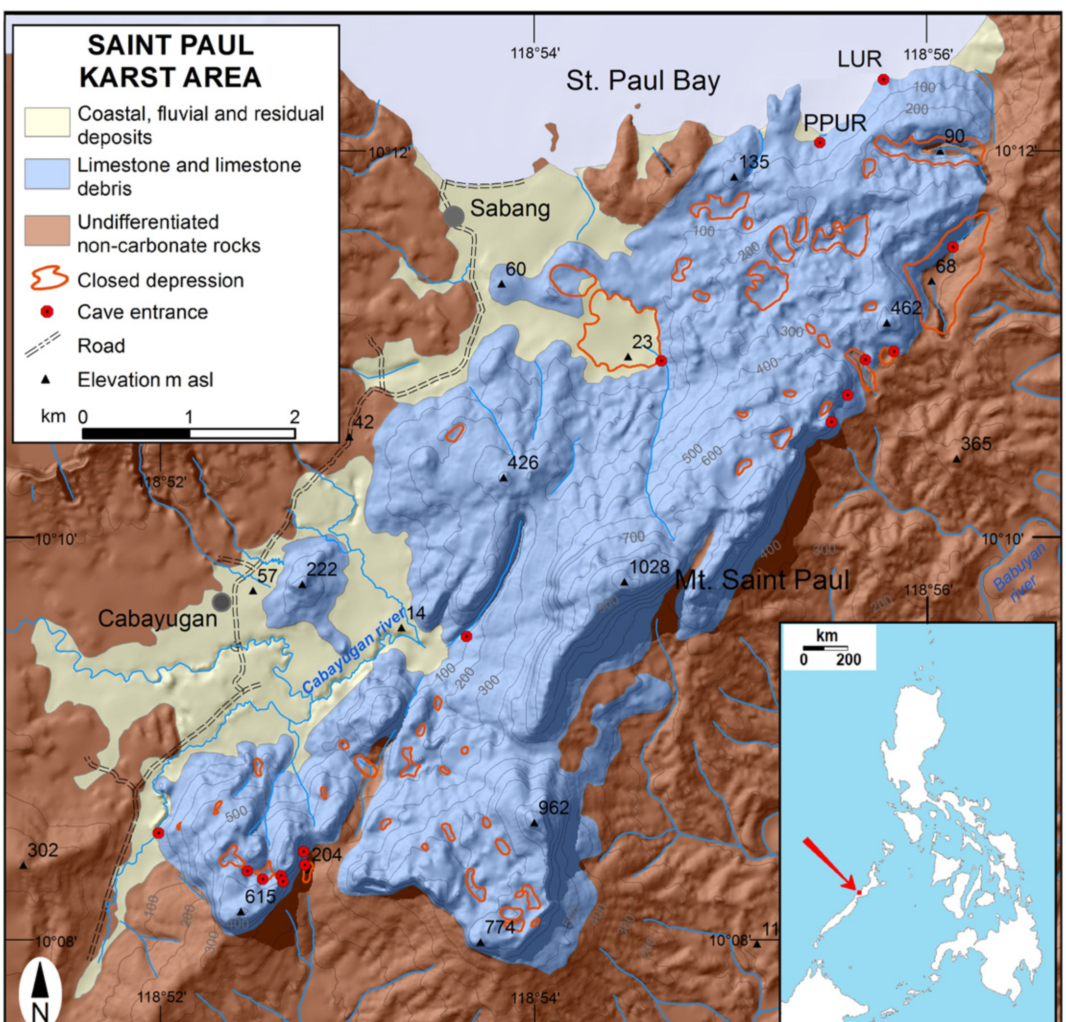

Fig. 1. Location map of the Saint Paul karst area. Location of the Puerto Princesa Underground River system (PPUR) indicated.