Estimating the growth rate in desert biological rock crusts by integrating archaeological and geological records

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Abstract. Biological rock crusts (BRCs) are ubiquitous features of rock surfaces in drylands composed of slow-growing microbial assemblages. BRC presence is often correlated with rock weathering, soiling effect, or with mitigating geomorphic processes. However, their development rate has not been quantified. In this work, we characterised and dated BRCs in an arid environment, under natural conditions, by integrating archaeological, microbiological and geological methods. To this end,
5 we sampled rocks from a well-documented Byzantine archaeological site, and the surrounding area located in the Central Negev Desert, Israel. The archaeological, which is dated to the 4th-7th centuries CE, was constructed from two lithologies, limestone and chalk. BRC started developing on the rocks after being carved, and its age should match that of the site. The BRC samples showed mild differences in the microbial community assemblages between the site and its surrounding, irrespective of lithology, and were dominated by Actinobacteria, Cyanobacteria and Proteobacteria. We further measured the BRC thickness,
10 valued at 0.1-0.6 mm thick BRC on the surface of 1700 years old building stone block of about 0.1 square metres. Therefore, a BRC growth rate was estimated, for the first time, to be 0.06-0.35 mm 1000 yr^{-1}. We propose that BRC growth rates could be used as an affordable yet robust dating tool in archaeological sites in arid environments.

1 Introduction

In arid and hyper-arid environments where abiotic processes are considered as the primary contributor to landform formation,
15 barren rock surfaces, free of vegetation, are a ubiquitous feature (Owen et al., 2011). These surfaces are exposed to multiple stress factors, such as lack of water, high radiation, and extreme temperature fluctuations, and therefore represent the edge of biotic existence on Earth (Viles, 2008). Such rock surfaces serve as a habitat for microorganisms by providing colonisation strata either on the outside (epilith; Pointing and Belnap, 2012), in the inner pores (endolith; Büdel and Wessels, 1991; Friedmann and Kibler, 1980) or underneath the rock (hypolith; Wierzchos et al., 2013). The microorganisms colonising rocks
20 form a hardy biomineral rock coatings known as a biological rock crust (BRC; Gorbushina, 2007), which is common in most arid and hyper-arid regions worldwide (Gorbushina, 2007; Lebre et al., 2017; Pointing and Belnap, 2012). From a microbial perspective, BRCs are typically colonised by actinobacteria, cyanobacteria and other phototrophic and heterotrophic bacteria,

yet they lack, or nearly lack, archaea, fungi, or algae (Lang-Yona et al., 2018). The influence of biota on landscapes is a topic that has remained mostly unexplored (Dietrich and Perron, 2006; Viles, 2019). BRCs were noted to play a crucial role in the
25 functioning of arid and hyper-arid environments, because of the limited activity of plants and of soil (Pointing and Belnap, 2012). A range of geobiological roles was suggested for BRCs including rock weathering (Garcia-Pichel, 2006; Warscheid and Braams, 2000), soiling effect (Viles and Gorbushina, 2003), deterioration of architectural heritage sites (Cabello-Briones and Viles, 2017) and mitigating geomorphic processes (Mcllroy de la Rosa et al., 2014). BRCs have also gained attention by astrobiologists, who point out that such communities when located in deserts, may act as analogs for possible life on Mars
30 (Corenblit et al., 2019). Yet, despite the suggested link between rock surface morphologies and microbial activity, one basic but important question remains unanswered: How quickly do BRCs develop after a rock surface has been exposed? Currently, there is no available information about the development rates of epi-and endolithic lithic biofilms on rock surfaces in deserts. Formation rates of sub-aerial BRCs were noted to be very slow (Pointing and Belnap, 2012), but were not backed by numbers. The goal of this study was to provide a first quantitative estimation to the growth rate of lithic communities on rock surfaces in
35 arid regions under natural conditions. Conventional dating methods like radiocarbon cannot be applied to these rock features owing to the lack of datable material. Cosmogenic radionuclide methods may be useful by yielding maximum-limiting surface exposure estimates. However, they require large amounts of sample material, which is destructive and therefore, unsuitable when dating archaeological sites or monuments. Lichenometry, which has been used extensively as a chronological tool in Arctic settings, is inapplicable for studying hot-desert geomorphology since deserts lack the moisture needed for lichen devel-
40 opment (Dorn, 2009; Mcllroy de la Rosa et al., 2014). To overcome these obstacles, we used a well-preserved archaeological site, build of stones that exhibit developed BRCs, marking the upper limit of the time frame needed for such processes to occur. Furthermore, because the nearby hillslopes were the source for the building stones, the features and composition of the BRCs can be compared to those under natural conditions. Owing to local environmental parameters, we predicted that both the BRC communities and features would differ between stones composing the archaeological buildings and natural stones in the adja-
45 cent slopes. To test our hypothesis, we combined field observations, geological, archaeological, and molecular microbiology characterisation to estimate the development rate and compositional trajectory of BRCs in arid regions.

1.1 Results

1.1.1 Geotechnical properties

BRCs were observed on all rock surfaces (i.e., limestone and chalk) both in the Byzantine site of Shivta and on the adjacent
50 slopes. To evaluate the geological differences between BRCs, we performed geological characterisation of 24 limestone- (Nezer Formation) and chalk- (Menuha Formation) samples. Table 1 depicts the geotechnical parameters tested, including mineralogy, total effective porosity and bulk density. Several large quarries, correlated with the Byzantine period (i.e., the Byzantine rule over Syria-Palestine 390-636 AD), are found within the chalk and limestone slopes of the Menuha and Nezer Formations in the northern Negev Desert (Fig. 1).
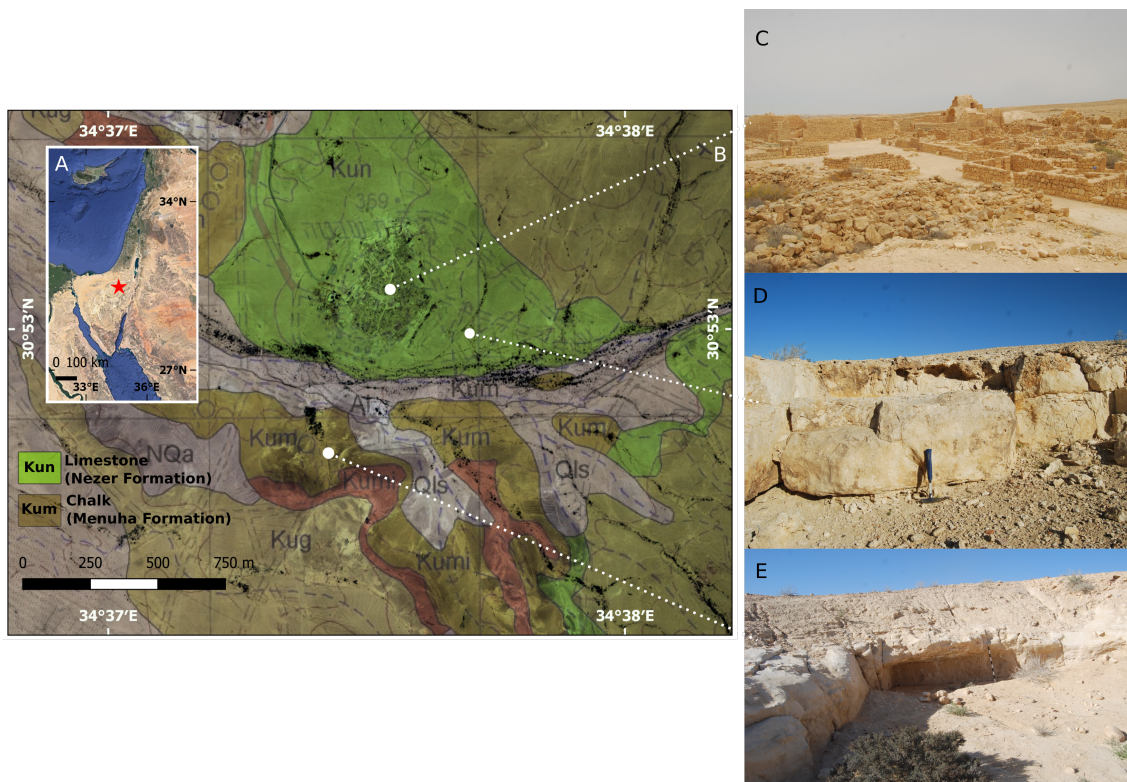
Figure 1. (A) Geographical location of the study area (red star) in the central Negev Desert, Israel (Google, ©2020 Landsat / Copernicus Data SIO, NOAA, U.S. Navy, NGA, GEBCO Mapa GISrael); (B) Shivta geological map (Sneh et al. (2011); reproduced with permission) (C) A panoramic view of Shivta Byzantine city; (D) Ancient limestone quarry located at the vicinity of Shivta Byzantine city (30 cm hammer for scale); (E) Ancient chalk quarry located at the vicinity of Shivta Byzantine city (1 m black and white stick for scale).

55   The limestone rocks constructing the Byzantine site were carved from the Turonian Nezer Formation; a well-bedded (30-50 cm) bio-micritic, fine to coarse-crystalline. Being well-bedded it is easily useable as a building material for different purposes (walls and ceilings). These blocks were lightly polished as they were used mainly as foundation of walls, leaving their original BRC intact. Accordingly, most rocks are were irregular in shape and were sealed with mortar covered with white lime plaster (Fig. 2).

60   The chalk blocks were carved from the Santonian Menuha Formation: a soft white massive chalk that was found applicable as a building material thanks to the ease of polishing it. In the carving process, new rock surfaces were exposed while building Shivta, leaving no remnants of the original BRCs. Soft chalk blocks were used mainly for building the upper parts of the walls (Fig. 2). Absence of plaster in between the chalk blocks, compared to the limestone blocks, indicate the intense polishing of these building blocks. Therefore, the carved chalk blocks could be considered succession planes for new microbial colonisers.
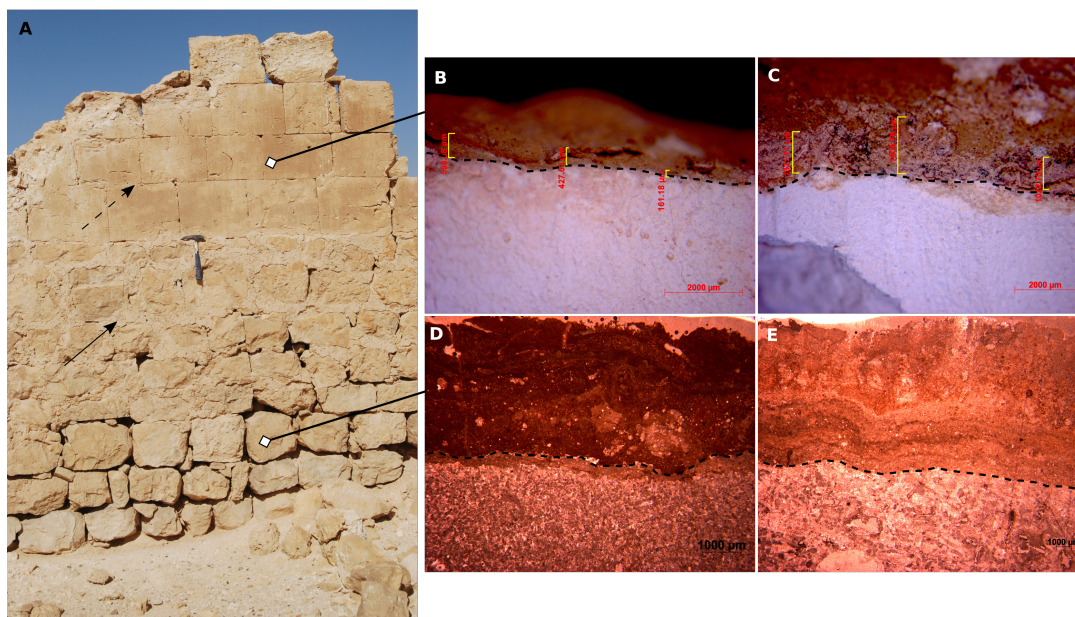
Figure 2. (A) Two rock types were retrieved from a south facing exterior wall (30 cm hammer for scale) in Shivta Byzantine city (1700 years old). The upper section of the wall was constructed of chalk blocks (dashed arrow), while the lower section was constructed of limestone blocks joined by plaster (solid arrow); (B) A thin BRC as observed in the chalk blocks from Shivta Byzantine city compared to a thicker BRC as observed in an an uncarved chalk rock from the adjacent slopes(C); (D, E) Limestone BRCs as observed in a sample collected from the city (D) and adjacent slopes (E). Dashed lines mark the border between the BRC and the host rock.

1.1.2 Thickness measurements

Microscopic examinations of thin sections (30 μm thick) that were prepared from the limestone and chalk blocks showed that, as expected, the BRCs were restricted to the atmospherically-exposed parts of the rocks (Wieler et al., 2019). The BRCs were characterised by a hardpan-laminated structure composed of masses of micritic to microsparitic carbonate layers interbedded with microbial coatings covering the lime and chalk host-rocks. BRC thickness significantly differed between those found on limestone compared to chalk building blocks, even when located on a single wall in the archaeological site (Table 1, Fig. 2). Limestone BRC thickness at both the Byzantine site and along the rock outcrops located in the limestone quarries at the adjacent slopes, ranged between 1.4–4.3 mm (Fig. 2D, 2E). In contrast, chalk BRC thickness differed between the blocks in the Byzantine site and the natural chalk slopes. The chalk BRC thickness at the Byzantine site ranged between 0.1–0.6 mm (Fig. 2B), while at the adjacent slopes, it ranged between 0.5–1.8 mm (Fig. 2C). The observed 0.1–0.6 mm BRC thickness upon the

75   chalk building blocks at the well-dated Byzantine site (dated between the 4th–7th centuries, CE), located under long stable arid

conditions and free of anthropogenic effects, suggest a growth rate of 0.06–0.35 mm 1000 yr^{-1}.

1.1.3   Isotopic composition

The biogenic nature of the crusts was confirmed using a cross-section analysis of the stable carbon and oxygen isotope ratios

in the crust and host rock. For the limestone sample, a shift was found between the δ^{13}C values for the BRC (0–2 mm) and

80   the host rock (2–5 mm) layers, with BRC values ranging between -4‰ and -5‰ and host-rock values between 0‰ and 1‰

(Fig. 3A). However, for the chalk, δ^{13}C values for the BRC ranged between -0.2‰ and -1.9 ‰, and between 0.1‰ and–2.7‰

in the host rock. These results were consistent for both the slope and archaeological site samples. The limestone δ^{13}C values

are typical indicators of carbon isotope exchange of primary marine $CaCO_3$ (abundant in the bedrock) with CO_2 released by

microbial respiration (i.e. of carbon originating from photosynthesis) with the subsequent precipitation of pedogenic calcrete

85   (Brlek and Glumac, 2014). The differences in δ^{13}C values between the chalk and limestone are suggested to result from the

BRC thickness. Thicker BRCs, as observed in the limestone samples, may hold more biogenic activity compared to the chalk.

The limestone δ^{18}O values ranged between -3‰ in the BRC to -7.3‰ in the host rock. This decrease in δ^{18}O values in the

host rock is suggested to result from meteoric water substitution of the marine limestone (Alonso-Zarza and Tanner, 2006).

The chalk δ^{18}O values ranged between -3.3‰ and -5.4‰ for both the BRC and the host rock, these negative $\delta18$O values were

90   consistent with other Santonian chalk (Clarke and Jenkyns, 1999; Liu, 2009).

1.1.4   Bacterial diversity of the BRCs in the Shivta Byzantine site and the nearby slopes

To elucidate the identity of the bacterial communities on the BRCs, we performed multiplexed barcoded amplicon sequencing

of the small subunit ribosomal RNA gene (SSU rRNA gene). As expected, we found simple BRC communities (i.e., low-

richness and low-diversity) in all BRC samples. Comparing the BRCs collected from the Byzantine site to the nearby slopes

95   from the two primary lithologies (the limestone and chalk) showed no statistically significant differences in the observed num-

ber of OTUs or their inverse Simpson or Shannon indices, with all samples averaging 312 ± 11 OTUs (Fig 4. A, Table S1). The

city samples did, however, show a slightly higher dominance of the most abundant OTU compared to the slope samples (BP

values of 0.24 ± 0.03 vs 0.14 ± 0.01; p=0.0017). The bacterial community composition of the BRCs was very similar in both

lithologies and sample sources and was heavily dominated by members of the phylum Actinobacteria, followed by Cyanobac-

100   teria, Proteobacteria (mainly Alphaproteobacteria from the orders Sphingomonadales and Rhodospirillales) and Bacteroidetes

(Fig. 4B). A variance partitioning analysis, did however, show a small difference between the samples from the city and the

ones from the slopes, explaining 8.1% of the variance in the Morisita-Horn distance matrix (p=0.023). In contrast, neither

the lithology nor the interaction between the lithology and sample source correlated with differences in bacterial community

composition (Fig. 4C, Table S2). These differences were not detected when comparing the dominance each phylum between

105   locations using Aligned Rank Transformed ANOVA test (Fig 4D). Instead, 64 individual OTUs were differentially more abun-

dant in the city samples while 58 were differentially more abundant in the slope samples (from a total of 732 OTUs; Fig S1).

These OTUs came from all the dominant phyla, with no discernible taxonomic pattern.
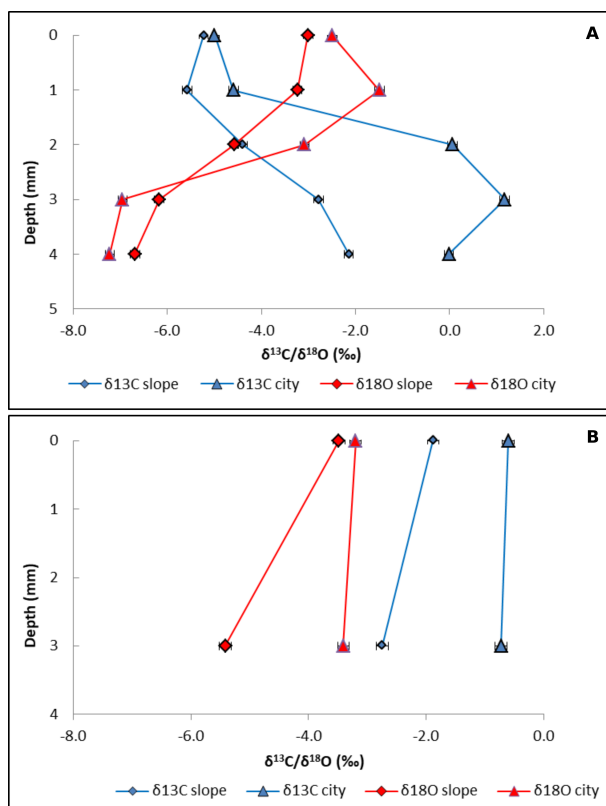
Figure 3. Carbon and oxygen isotopes profiles in BRCs and host rock samples of limestone (A) (Nezer Formation) and chalk (B) (Menuha Formation) samples collected from the Shivta site (triangles) and adjacent slopes (diamond).
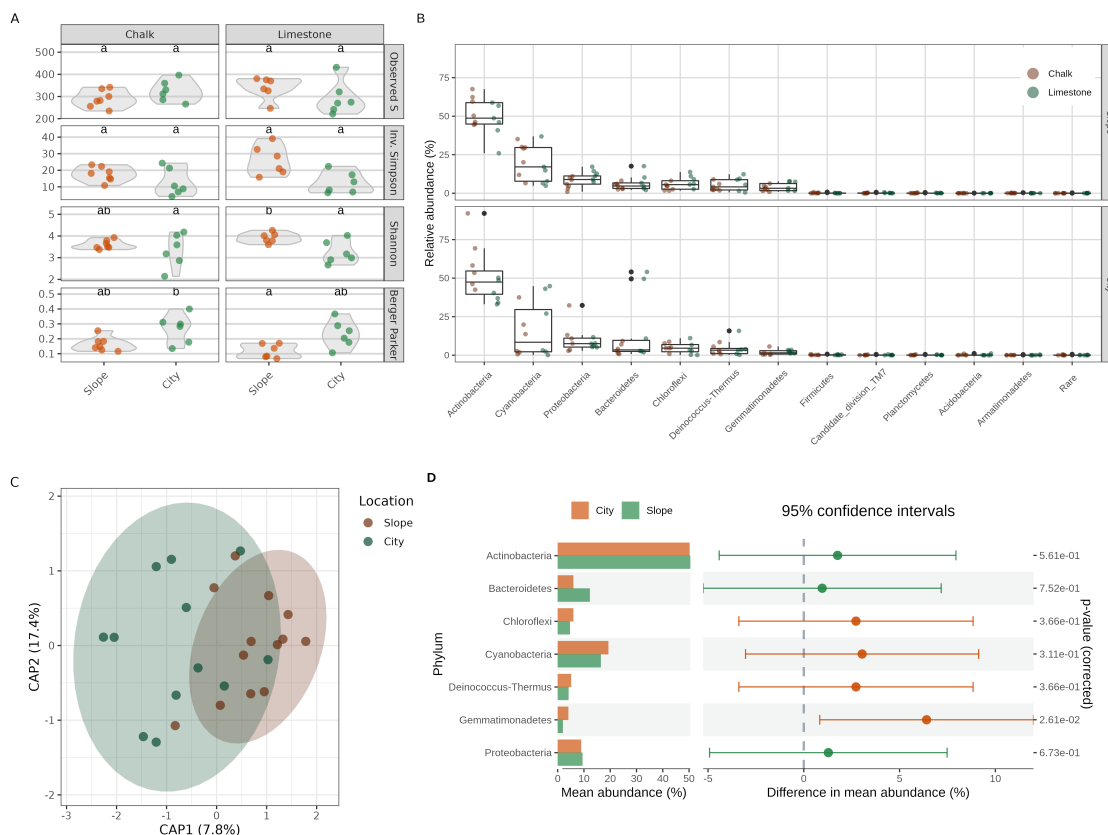
Figure 4. (A) Bacterial alpha-diversity indices (Observed S, Inv Simpson, Shannon and Berger Parker) for chalk and limestone BRCs. Different lower-case letters denote statistical difference. (B) Bacterial community composition in the chalk and limestone BRCs sampled from the Shivta Byzantine city and adjacent slopes. 'Rare' denotes all OTUs belonging to phyla that account for less than 5% of the relative abundance. (C) Canonical analysis of principal (CAP; i.e. constrained principal coordinates analysis) method showing the differences in bacterial community composition in limestone and chalk BRCs collected from the city and nearby slopes (n=24). The numbers in brackets indicate the explained variance in the constrained model (Morisita-Horn distance as a function of location). (D) Differences in mean abundance, 95% confidence intervals and statistical significance (based on ART-ANOVA) on the phylum level between slope and city samples (only phyla that account for more than 5% of the relative abundance are shown).

1.2 Discussion

BRCs are a common and important feature of atmospherically-exposed rock surfaces in drylands around the globe, yet reliable
110 growth estimations based on field data are rare. Only a handful of studies tried to estimate BRC growth rates, among them
Lange (1990) measured radial growth rates of epilithic lichens in the arid Negev Desert, Israel, and reported an average growth
rate of 0.371 mm yr⁻¹. Another study conducted by Krumbein and Jens (1981) found that desert varnish, a typical rock crust
in desert regions, show black fungi microcolonies after eight weeks isolation in the lab. Liu and Broecker (2000) noted the

accumulation rates of desert varnish in natural conditions to be much slower, in the range of <0.001 to 0.04 mm kyr^{-1}, and

115 rarely reach thickness exceeding 200 μm.

In this study, we observed 0.1–0.6 mm thick biological rock crust coverage on chalk building blocks of the Byzantine site (Fig. 2B) dated to the 4th–7th centuries CE (Tepper et al., 2018). The building blocks experienced long stable arid conditions and were free from direct anthropogenic influences. Thanks to the processing method of the bricks used for construction, leaving a BRC-free surfaces exposed to the elements, hence, the BRC is confined by the dating of the archaeological site (Tepper

120 et al., 2018). This provides us with an estimated growth rate of 0.06–0.35 mm 1000 yr^{-1} for BRCs of primarily bacterial origin. Besides, the presence of a 1.4–4.3 mm thick BRC in all limestone rocks (Fig. 2D, 2E) and 0.5–1.8 mm on the chalk rocks collected from the slopes (Fig. 2C), provide a plausible maximum for BRC growth under these conditions.

From a microbiological perspective, all the samples studied here showed very similar microbial community composition, irrespective of lithology or BRC thickness. This similarity in composition demonstrates the indifference of microorganisms to

125 the type of attachment surface in this case and that the community probably changes very little after establishing. However, the differences in BRC thickness between the chalk and limestone sampled from the slopes could indicate that the latter can better support BRC growth.

Differences in the dominance of the most abundant OTU as well as some differences in the relative abundance of about 17% of the OTUs were observed between BRCs from the city and slope samples. However, these differences were relatively minor and

130 lacked a clear taxonomic pattern. Overall, the results point to a very deterministic successional course of BRCs development on rock surfaces. Moreover, the similarly in the microbial composition between rocks that were in contact with the ground to the those that were detached from the ground (chalk BRCs found in Shivta), indicate a major role to aeolian processes in determining the community composition of BRCs in deserts as was previously reported (Wieler et al., 2019).

Assisted recovery of lithobiontic communities has not been conducted in natural settings, and most research focused on the

135 regeneration of soil biocrust (Velasco Ayuso et al., 2017). Artificial cultivation of soil biocrusts (Zhang et al., 2018) suggest that inoculation of cyanobacteria and algal communities enhance the recovery of biocrusts. Testing the soiling impact on rock surfaces, suggest that bacterial colonisation play an important part in the development of fungal biofilms (Viles and Gorbushina, 2003). In fact, cyanobacteria and fungi are believed to be critical components of soil and rock biocrusts (Gorbushina, 2007; Weber et al., 2016). In arid BRCs fungi are scarce (Lang-Yona et al., 2018), but our results suggest that not only Cyanobacteria,

140 but other taxa like Alphaproteobacteria and Actinobacteria, play a key role in BRC development (Fig. 4B). Similarly, the dominance of Alphaproteobacteria and Actinobacteria in early soil biocrusts formation was observed in arid regions (Ji et al., 2017; Pepe-Ranney et al., 2016).

Unlike more humid dryland soils, in hyperarid soils and rock biocrusts, Actinobacteria remain the dominant phylum even in later stages of development (Holmes et al., 2000; Angel and Conrad, 2013; Idris et al., 2017). Kuske et al. (2012) identified

145 a deep branching subclass within the Actinobacteria phylum abundant worldwide, the Rubrobacteridae, a taxon extremely resistant to desiccation and UV stress (Holmes et al., 2000; Rainey et al., 2005). The presence of Rubrobacteridae suggests that they may be involved in shaping the rock surface structure during biocrust formation (Mummey et al., 2006; Rainey et al., 2005).

Our analyses invalidate the lithology role in shaping the BRC composition, as both rocks experience the same regional-scale
150 environmental factors (Fig. 4C). This demonstrates the ecological filtering effect of the rock surfaces, which imposes unique
abiotic challenges for the inhabiting microbes, and infer that dust particles are the main potential source for the microbial
communities (Wieler et al., 2019). We thus suggest that local-scale environmental parameters play a major role in shaping the
microbial taxa that colonize fresh rock surfaces in arid regions. This also suggests that the BRCs cannot be regarded as passive
deposits of microbial cells, but should rather be seen as a filter selecting for specific subset of adapted microbes that can persist
155 and form a biofilm under these harsh conditions.

Applying stable isotopes, we noted a consistent trend where more negative δ^{13}C values were found in the limestone crust
compared to their host rock (Fig. 3A), reflecting a biogenic agency in the rock crust production, regardless of the substrate
type. The oxygen isotopes profile of the chalk samples collected from the archaeological site, showed no difference between
the bedrock and the crust (Fig. 3B), thus, it indicates early stages of BRC formation. The limestone samples, showed more
160 negative δ^{13}C values in the BRC compared to the host rock. Yet, the δ^{18}O values were more negative at the host rock compared
to the BRC, which may indicate sub-aerial exposure of the BRC and substitution of the marine limestone.

1.3 Conclusions

This study provides the first estimate to an unfathomed question on the rate of biological rock crust growth rate under natural
setting. The growth rate observed here, validates the extremely slow nature of such a succession process. Using a well-dated
165 archaeological site in the arid Negev Desert, Israel, we demonstrate the possibility of using such human-made artefacts to doc-
ument and confine long microbial developmental processes, that are otherwise too slow to monitor. Conversely, once a growth
rate has been established for a region, it could be used, by itself, to date the age of atmospherically exposed archaeological
artefacts.

1.4 Materials and methods

170 To estimate BRC development rate, we applied a quantitative analysis comparing microbial communities from chalk and
limestone rocky slopes to their equivalents in a dated archaeological site, the Byzantine city of Shivta (Fig. 1). The methodology
of this study involves applying archaeological, geological and microbiological methods on collected BRC coated rocks.

1.4.1 Study site

Shivta is an exceptionally well-preserved village of the Byzantine period (4th–7th centuries CE) that continued to be partially
175 occupied into the Early Islamic period (8th-9th centuries CE; Avni, 2014). Shivta is located in the south-western regions of
the Negev Desert, Israel, at an elevation of 350 m.a.s.l (30.88°N; 34.63°E; WGS 84 Grid; Fig. 1) where the environmental
settings maintain arid conditions since the Holocene (10,000 years ago) and characterised by an average annual precipitation
of 90 mm yr^{-1} and an aridity index (P/PET) of 0.05, on the borderline between arid and hyperarid ecosystems (Amit et al.,
2011). The site and its vicinity are part of a rocky terrain, underlined predominantly by carbonate rock slopes. Limestone

180   bedrock outcrops of the Turonian Nezer Formation and soft chalk outcrops of the Santonian Menuha Formations surround the city (Fig. 1). BRCs are common on the atmospherically-exposed parts of many of the rocks. The site covers an area of 0.8 km² and contains the remains of three churches, a central watch tower and associated structures, two sizeable public water reservoirs, three wine-presses, a large inn of the Byzantine period and numerous private buildings. The main occupation of the residents in the Byzantine period appears to have been agricultural, mainly viticulture for the export of wine, and road services

185   for Christian pilgrims travelling to and from Mt. Sinai (in modern-day Egypt). Thanks to these activities, the village appears to have been very prosperous in the Early and Middle Byzantine periods (4th-mid-6th centuries CE) when most of the village was constructed. Excavations in the site in 2016 conducted by a team led by G. Bar Oz and Y. Tepper on behalf of Haifa University, have confirmed the date of the construction of private houses in the southeastern part of the town (Tepper et al., 2018). Their excavations extended to the bedrock under several houses over which the structures were constructed. The location of the

190   village in an arid setting in the central Negev Highlands forced the inhabitants to construct buildings using locally quarried stone with a minimum use of wood, which would otherwise had to be imported from great distances. Therefore, the upper floors were supported with stone arches and wood was sparsely used for doorframes, doors and shelves. In lieu of wood, many installations, such as animal troughs, were carved from local stone. The walls of the houses are well-preserved, offering researchers a unique view of buildings constructed over 1700 years ago that stand to heights of two and even three stories high.

195   The lower courses of the walls on the ground floor were made using rough limestone blocks, taken from Nezer Formation, while the upper walls were constructed of a lighter chalkstone, taken from Menuha Formation that is more easily worked into blocks. The spaces between the heavy stones of the lower courses were sealed with mortar, and the interior walls were often covered with a base of mud plaster covered with white lime plaster (Fig. 2).

1.4.2   Field sampling

200   A total of 24 rock samples were collected from Shivta Byzantine city (30.88°N; 34.63°E; WGS 84 Grid; the samples were named ShivtaSite 1-12) and its surroundings (30.87°N; 34.62°E; WGS 84 Grid; the samples were named ShivtaSlope 1-12). Twelve rock samples were collected from the limey Nezer Formation including six samples from the archaeological site and six from the nearby natural slope. The same sampling procedure was applied for the chalky Menuha Formation. To avoid the slope aspect effect that may lead to different moisture regime, all samples were retrieved from a south-facing slopes/walls and

205   were collected during January 2015.

1.4.3   Geological analysis

The geological methods used in this study are based on direct field observations and characterisation of the subjected lithologies (i.e., Limestone and Chalk) using thin sections, XRD analyses, total effective porosity and stable isotope analysis. Petrographic thin sections, 30 μm thick, were prepared for each lithology to test the main components in both the rock crust and the host

210   rocks examined under a light microscope (Zeiss, Oberkochen, Germany). XRD analyses for bulk mineralogical components (Sandler et al., 2015) were conducted separately on the rock crust and on the host rock, three replicates were collected from each lithology. Powdered samples were scanned by a PANALYTICAL X'Pert3 Powder diffractometer equipped with a PIXcel

Table 1. Biological rock crust (BRC) thickness and geotechnical properties of the subjected strata

Rock properties		Chalk[1]	Limestone[2]
BRC mineralogy (%)	Calcium	92	95
	Quartz	2	4
Host rock mineralogy (%)	Calcium	95	95
	Quartz	0	0
Host rock porosity (%)		26	7.1 ± 0.7
Host rock bulk density (g cm-3)		1.95 ± 0.1	2.5 ± 0.1
BRC thickness	Shivta Byzantine city	290 ± 181	3206 ± 632
(μm) n=6	Bedrock slopes	1279 ± 429	2585 ± 930

[1] The chalk was dated to the Menuha formation

[2] The limestone was dated to the Nezer formation

detector. Scanning range was: 3–70° 2θ , step size 0.013°, speed 70.1 s per step. Total effective porosity (ϕ) (Scherer, 1999) was performed using a gas permeameter and porosimeter device (Core laboratories, Amsterdam, Netherlands) on 12 rock core cylinder samples (radius 18.5 mm and height 26.5 mm). The value of chalk total effective porosity was cited from Schütz, et al., (2012) and reported in Table 1.

For the stable isotopes δ^{13}C and δ^{18}O analyses, 1-2 mg of rock surface powder was obtained using a microdrill (Dremel, Racine, WI, USA) along a cross section of the rock crust and its host rock. Six profiles measurements of δ^{13}C and δ^{18}O were performed on the chalk and limestone samples. Measurements (in duplicate) of δ^{18}O-H$_2$O and δ^{13}C-DIC were performed on gas source isotope ratio mass spectrometer (GS-IRMS; Thermo Fisher Scientific, Waltham, MA, USA) coupled to a Gas Bench II interface (Thermo) after CO$_2$ equilibration or CO$_2$ extraction by acidification for δ^{18}O-H$_2$O and δ^{13}C-DIC, respectively. The samples were calibrated against internal laboratory standards: Vienna Standard Mean Ocean Water (VSMOW) and carbonate standard NBS19. δ^{13}C values were also referenced against VSMOW and valued for carbonate relative to Vienna PeeDee Belemnite (VPDB) standard as previously described (Uemura et al., 2016) with SD of 0.1‰. All values are reported in per-mil (‰).

1.4.4 DNA Extraction PCR amplification and sequencing

For DNA extraction from rocks, the surface (ca. 100 cm^2) was scraped off using a wood rasp (66-67 HRC hardness; Dieter Schmid, Berlin, Germany) that was cleaned with 70% technical-grade ethanol before each sampling. DNA was then extracted using 0.4 g of sample using Exgene Soil DNA extraction kit (GeneAll, Seoul, S. Korea) according to the manufacturer instructions. A 466-bp fragment of the SSU rRNA gene was amplified using the universal bacterial primers 341F

(CCTAYGGGRBGCASCAG) and 806R (GGACTACNNGGGTATCTAAT) flanking the V3 and V4 region (Klindworth et al., 2013). Library construction and sequencing were performed at a DNA Services Facility (University of Illinois at Chicago, USA) using a MiSeq sequencer (Illumina, San Diego, CA, USA) in the 2 × 250 cycle configuration (V2 regent kit). The
235 raw SRA files were deposited into EMBL- ENA SRA database (https://www.ebi.ac.uk/ena/) and can be found under study accession PRJNA381355.

1.4.5 Sequence processing and analysis of bacterial communities

Paired reads generated by the MiSeq platform were quality filtered and clustered into OTUs using the UPARSE pipeline (Edgar, 2013), with modifications. Contig assembly was done using the fastq_mergepairs command. Then, contigs were dereplicated
240 with the derep_fullength command, and singleton sequences were removed. OTU centroids were then determined with the cluster_otus command (set at 3% radius). Abundances of OTUs were determined by mapping the filtered contigs (before dereplication, including singletons) to the OTU centroids using the usearch_global command (set at 0.97% identity). Following these steps, a total of ca. 1.4 million reads remained. OTU representatives were classified using mothur's implementation of a Naïve Bayesian sequence classifier (Schloss et al., 2009; Wang et al., 2007) against the SILVA 119 SSU NR99 database (Quast
245 et al., 2013). All downstream analyses were performed in R V3.4.4 (R Core Team, 2020). Data handling and manipulation were done using package phyloseq (McMurdie and Holmes, 2013). For alpha-diversity analysis, all samples were subsampled (rarefied) to the minimum sample size using bootstrap subsampling at 1000 iterations, to account for library size differences, while for beta-diversity analysis library size normalisation was done using GMPR (Chen et al., 2018). The Inverse Simpsons, Shannon's H diversity indeces and the Berger-Parker dominance index were calculated using the function EstimateR in the
250 vegan package (Oksanen et al., 2018) and tested using ANOVA in the stats package, followed by a post-hoc Estimated Marginal Means test (Searle et al., 1980) from the emmeans pacjage (Lenth et al., 2020). Variance partitioning and testing were done using PERMANOVA (McArdle and Anderson, 2001) function vegan::adonis using Horn-Morisita distances (Horn, 1966). Differences in phyla composition between the sample type were tested using the non-parametric igned Ranks Transformation ANOVA (ART ANOVA; Wobbrock et al., 2011) in the package ARTool, and FDR corrected using the Benjamini-Hochberg
255 method (Ferreira and Zwinderman, 2006) (function stats::p.adjust). Detection of differentially abundant OTUs was done using a beta-binomial regression model (Martin et al., 2019) in the package corncob. Plots were generated using packages ggplot2 (Wickham, 2016). The scripts for reproducing the microbial analysis can be found at: https://github.com/roey-angel/BRC_growth_microbiome.

Code availability. https://github.com/roey-angel/BRC_growth_microbiome

260 *Data availability.* https://www.ncbi.nlm.nih.gov/bioproject/PRJNA381355

Appendix A: Supplementary figures and tables

Table A1. ANOVA test results for various alpha-diversity metrics.

Observed S	Sum Sq	Df	F value	Pr(>F)	
(Intercept)	588166	1	198.58	3.60E-12	***
Location	3993	1	1.35	0.26	
Rock.type	7767	1	2.62	0.12	
Location:Rock.type	10123	1	3.42	0.08	
Residuals	62200	21			
Inv. Simpson					
(Intercept)	4281315	1	1306.61	2E-16>	***
Location	4	1	0	0.97	
Rock.type	1671	1	0.51	0.48	
Location:Rock.type	8756	1	2.67	0.12	
Residuals	68810	21			
Shannon's H					
(Intercept)	308.9	1	1353.08	2E-16>	***
Location	1.4	1	6.1	0.02	
Rock.type	0.1	1	0.36	0.55	
Location:Rock.type	0.3	1	1.15	0.3	
Residuals	4.8	21			
Berger Parker					
(Intercept)	7346	1	145.56	6.60E-11	***
Location	543	1	10.76	3.60E-03	**
Rock.type	99	1	1.96	0.18	
Location:Rock.type	117	1	2.32	0.14	
Residuals	1060	21			

Table A2. Variance partitioning of the Morisita-Horn distance matrix using PERMANOVA

Observed S	Df	Sums of Sqs	Mean Sqs	F Model	R2	Pr(>F)	
Location	1	0.63	0.63	2.12	0.08	0.02	*
Rock.type	1	0.39	0.39	1.3	0.05	0.23	
Location:Rock.type	1	0.49	0.49	1.63	0.06	0.1	
Residuals	21	6.25	0.3	0.81			
Total	24	7.75	1				
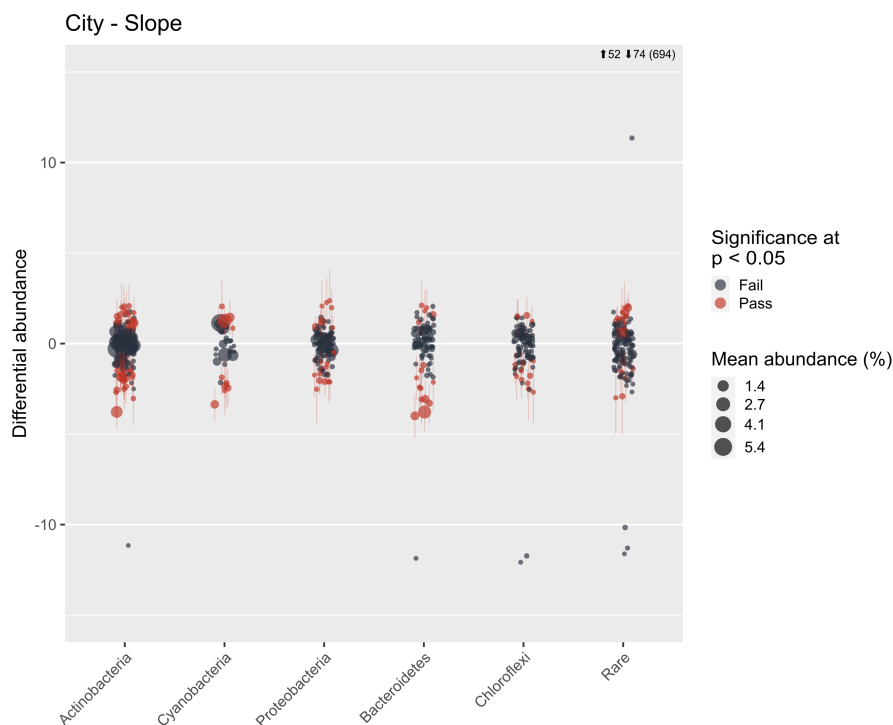
Figure A1. Detection of differentially abundant OTUs between the city and slope samples using a beta-binomial regression model (corncob). Each circle denotes a single OTU, and its size is its average relative abundance across all samples. The x-axis shows the classification of each OTU, whereas the y-axis denotes the difference in the modelled mean relative abundance between the city and slope samples. 'Rare' denotes all OTUs belonging to phyla that account for less than 5% of the relative abundance. Red circles are OTUs that show significant differential abundance at the P <0.05 level. Numbers next to the arrows (top right) indicate the number of significant differentially abundant OTUs that are either more abundant (up arrow) or less abundant (down arrow) in the city samples compared to the slope samples. The number in brackets indicates the total number of OTUs tested.

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265   NW, TG, OG and RA wrote the paper. OG and RA contributed equally to this study.

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