THE CONTRIBUTION OF CONDENSATION-CORROSION IN THE MORPHOLOGICAL EVOLUTION OF CAVES IN SEMI-ARID REGIONS: PRELIMINARY INVESTIGATIONS IN THE KYRENIAN RANGE, CYPRUS

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Abstract


The condensation-corrosion process occurs when airflow cools at the contact with colder cave walls. Condensed water becomes aggressive for soluble rocks and corrodes the walls. This process is particularly active close to cave entrances in high thermal gradient zones where external air enters caves. Condensation ap-

Izvleček


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INTRODUCTION

The condensation-corrosion process corresponds to the dissolution of cave walls by condensation water brought by external airflow crossing caves and cooling on colder walls. This widespread process is particularly efficient in relict caves, close to entrances where the thermal gradient is high, in alpine caves where airflow is substantial, in the upper levels of cave or close to the ceiling where air is warmer (Badino 1995, 2010), or in hypogene caves when corrosion is enhanced by the presence of acids. It is far more active in summer when cooling of surface air entering caves can produce significant amounts of condensation; in contrast, condensation is very limited in winter, except in alpine caves when air rising through vertical caves cools and produces condensation in upper entrances, at the contact of the rock cooled by the ambient winter temperature (Klimchouk et al. 1996; Dublyansky & Dublyansky 2000). Several studies have shown the relative importance of condensation water volume: in the Crimea region, it represents 3.5% of the total spring discharge and 4.5 L/s/km² in summer (Dublyansky & Dublyansky 2000), 0.7 L/s in the Sorbas semi-arid region, Spain (Sanna et al. 2015), 0.15 L/s in Spipola Cave, Italy.
Condensation acquires its aggressiveness from \( \text{CO}_2 \) in the cave air and becomes corrosive for the limestone walls (Dreybrodt et al. 2005). Wall retreats have been calculated, theoretically (Dreybrodt et al. 2005), from field climate records (Dublyansky & Dublyansky 2000), from corrosion measures on limestone tablets (after P.M. Avramides in James 2013; Tarhule-Lips & Ford 1998a), and from uranium-thorium (U/Th) dating on corroded speleothems (Auler & Smart 2004). These studies suggest a wall retreat range from 0.3 to 30 mm/ka. In Sorbas gypsum caves, wall retreat has been estimated to be 22–33 mm/ka (Klimchouk et al. 1996; Gázquez et al. 2015; Sanna et al. 2015). In extreme environments, such as in hypogene caves with high concentration of acidic gas and high thermal gradient, the intensity of condensation-corrosion and of the wall retreat is 1 to 2 orders of magnitude larger (Lismonde 2003; Dublyansky & Dublyansky 2000 and references therein). Special attention has recently been given on caves occupied by large bat colonies. The metabolism of bats and the mineralization of guano produce \( \text{CO}_2 \), vapour, and heat. Together, they contribute to the increase of the condensation-corrosion process with a wall retreat reaching up to 34 mm/ka. In some peculiar cases, bat-related condensation-corrosion appears to be the main process of cave enlargement (Lundberg & McFarlane 2012, 2015). The morphologies related to this process are cupolas, bell holes, flutes, megascallops, pendants, karrens, ceiling channels, corroded or weathered walls, boxwork, and potholes (Cigna & Forti 1986; Jameson 1991; Tarhule-Lips & Ford 1998a, b; Auler & Smart 2004; Lundberg & McFarlane 2009; Miller 2014; Fabbri et al. 2017; Frumkin et al. 2018; Audra et al. 2016 and references therein).

The condensation-corrosion process, enhanced by airflow convections, shapes rounded features (such as ceiling channels, niches, convection cupolas, and megascallops), which are almost similar to the phreatic morphologies in “classical” cave passages. The superimposition of features associated with both processes is frequent and occurs successively, first by phreatic and then aerial processes. Therefore, measuring the condensation-corrosion process separately is difficult in caves initially formed in a phreatic context, thus making the quantification of this particular process challenging. Therefore, the condensation-corrosion process has been under-estimated as a significant morphogenetic process, compared to phreatic flow, which is indeed widespread.

The Kyrenia Range is located along the northern coast of the island of Cyprus, paralleling the northern shore (Fig. 1). The Kyrenia Range, a 160 km long, narrow mountain range with a maximum elevation reaching 1000 m a.s.l., was subject to a rapid uplift and aerial exposure only since the Upper Pliocene. Most of the caves found in the range are therefore of tectonic origin, not dissolitional karstic, comprising original rounded voids that were never under phreatic conditions. Thus, this Mediterranean region and its related caves provide an excellent focus for the investigation of “rounded” features linked to condensation-corrosion by airflow convections.

In this paper, we analyse the condensation-corrosion features of five caves in carbonate and gypsum rocks located in the Kyrenia Range, Cyprus, in order to: i) define the morphological features as an expression of cave genesis; ii) characterize the morpho-tectonic evolution; iii) assess the role of condensation-corrosion as a major late stage process in semi-arid climate; iv) highlight the role of bat colonies and guano deposits.

THE KYRENA RANGE (GEOLOGY, GEOMORPHOLOGY, CLIMATE, VEGETATION)

Cyprus is located in the Levantine Basin, in the Eastern Mediterranean region (35°N; 33°E). It is the third largest island in the Mediterranean Sea, with a surface of 9250 km\(^2\) (Fig. 1). Three major physiographic units characterize the island. The Troodos Mountain is the main mountain range on the island, reaching 1951 m a.s.l. (Mt. Olympus). The narrow belt (6 km wide and 160 km long) of the Kyrenia Range along the northern coastline rises to 1023 m a.s.l. to the West (Kronos Peak), and lowers eastward until the tip of the Karpas Peninsula. Both ranges are separated by the Mesaoria Plain, which has an average altitude of 100 m a.s.l. (max. 325 m a.s.l.), and where Nicosia, the capital city, is located.

Cyprus is at the junction of the African Plate to the South, the Anatolian microplate to the North, and the Arabian Plate to the East (Fig. 2a). The Kyrenia Range is mainly composed of Triassic to Cretaceous limestones and dolomitic limestones, recrystallized in marbles (Constantinou 1995). To the south of the Kyrenia range, the Mesoaria Plain is filled with mainly marine sediments dated from the Paleogene to Quaternary. The present-day island structure expresses dextral movements associated with the northward motion of the African and Arabian
plates that were at the origin of the westward escape of the Anatolian microplate, with permanent and significant seismic activity (up to 6.5 magnitude). The orogenesis of the Kyrenia Range occurred in the Late Miocene / Early Pleistocene, when the southern margin of the Anatolian microplate folded and overthrust onto the Troodos massif with a left-lateral and transpressunal regime. A regional uplift intensified during the Early Pleistocene, controlled by under-thrusting of continental crust from the south (Constantinou 1995; Palamakumbura & Robertson 2016; Harrison et al. 2013). The carbonate Trypa Formation ranging from the Triassic in the north to the Cretaceous in the south settled as subvertical slabs and narrow folds that preserve more recent chalky layers from the Lapithos Formation, from Cretaceous to Eocene (Fig. 2b). The center of the Kyrenia Range landscape is marked by the Kyrenia Crest with olistostrome of permo-carboniferous Kantara limestones. The southern edge is overthrust over the Cenozoic Kythrea Formation of the south (Constantinou 1995; Palamakumbura & Robertson 2016; Harrison et al. 2013). The carbonate Trypa Formation ranging from the Triassic in the north to the Cretaceous in the south settled as subvertical slabs and narrow folds that preserve more recent chalky layers from the Lapithos Formation, from Cretaceous to Eocene (Fig. 2c). The northern edge of the range comprises limestone bars covered with sediments, from Cenozoic to recent formations (McCay & Robertson 2013).

The climate of Cyprus is semi-arid with mean monthly temperatures ranging from 21 °C along the coast to 15 °C on top of the Kyrenia Range. Temperature maxima can reach 35–45 °C in the Mesaoria Plain. Rainfall is mainly concentrated in the winter season (October to March), with annual minima of 342 mm in the sheltered Mesaoria Plain and up to 550 mm annually on the Kyrenia Range, which acts as a barrier for the northern marine winds (Fig. 5). The evapotranspiration reaches 90% with a small specific recharge amount of 4 L/s.km² for the wettest reliefs. In a tectonic context of extreme fracturation, the infiltration occurs over 85 km² along a narrow carbonate range and eventually reaches very small overflow springs located at the foot of the range near archeological and historical sites: Kythrea, Bellapais, Lapithos, Krini, and Karavas (Unit of Environmental Studies 2018).

The vegetation cover in northern Cyprus is typical of the semi-arid climatic East-Mediterranean region. It is mainly composed of herbaceous and garrigue forests on the lower slopes. The summits of the northern slopes are covered with pines and cypress forest and degraded Mediterranean scrub after repeated fires. The Kyrena carbonates seem to be poorly karstified, according to the dry climatic conditions, the limited outcrops along the crest, the diffusion of seepage across nu-
Fig. 2: Geology of Cyprus. A) Kyrenia Range is part of the Anatolian microplate, thrust southward onto the Troodos ophiolites. Kyrenia Crest is made up of subvertical Mesozoic carbonates, and in the eastern part of a Permian limestone olistostrome. B) and C) Geological profiles over sections, indicated on the map A). Data on A) and C) obtained from Cleintuar et al. (1977), and B) from McCoy & Robertson (2013).
Numerous fractures, and the partitioning of catchments by faults. On the surface it is limited to recent rainfall karren and no typical solution caves were observed. Only some calcite hydrothermal veins associated with early tectonic phases prior to emersion have been identified in marble brecciated zones above St. Magar monastery.

### STUDIED CAVES AND METHODOLOGY

Almost 200 caves are recorded in Cyprus (Gucel 2018) and can be grouped in three different types: i) fracture-caves mainly located in massive carbonates (Kyrenia); ii) gypsum caves located in the Messinian gypsum of Mesaoria basin; iii) marine caves located in recent calcarenites (Fig. 1). The caves are of moderate extension. Currently, Fig Tree Cave (“İncirli Show Cave”) is the longest cave in Cyprus (365 m), while the deepest is Pentadakty-

<table>
<thead>
<tr>
<th>Name of Cave</th>
<th>District</th>
<th>Coordinates</th>
<th>Altitude (m a.s.l.)</th>
<th>Vertical range (m)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoky Cave</td>
<td>Kyrenia</td>
<td>35.311947°N 33.592556°E</td>
<td>790</td>
<td>35</td>
<td>93</td>
</tr>
<tr>
<td>Pigeons Cave</td>
<td>Famagusta</td>
<td>35.421372°N 33.958214°E</td>
<td>477</td>
<td>30</td>
<td>870</td>
</tr>
<tr>
<td>First Day Cave</td>
<td>Famagusta</td>
<td>35.322167°N 33.793594°E</td>
<td>265</td>
<td>=5</td>
<td>79</td>
</tr>
<tr>
<td>Angry Bat Cave</td>
<td>Famagusta</td>
<td>35.322678°N 33.797353°E</td>
<td>310</td>
<td>17</td>
<td>110</td>
</tr>
<tr>
<td>Fig Tree Cave</td>
<td>Famagusta</td>
<td>35.324947°N 33.769764°E</td>
<td>245</td>
<td>25</td>
<td>365</td>
</tr>
</tbody>
</table>
los Cave (-200 m). Caves generally host bat colonies and pigeons that produce thick guano deposits. We studied five caves from type i) and ii) (Tab. 1).

THE CAVES IN MASSIVE PERMO-CRETACEOUS CARBONATES (TYPE [I])

Most of the caves are orientated N30°E and correspond to large open-fractures combined with the E-W transpressive faults. These N30°E fractures are strike-slip faults that end up as pull-apart openings (Harrison et al. 2008). Some of these openings became fracture-caves, with an initial preserved morphology: mechanical fracture-guided passages, rough and planar walls and ceilings, no trace of any concentrated water flow or fluvial sediments. Due to recent tectonic activity and gravity release movements, subsequent breakdown blocks are covering the bottom-end of shafts. Few of the recent developed fractures derive from decompression near cliffs, even if caves are very close to steep slopes or cliffs because of the thinness of the range. Most fracture-caves are several meters wide and generally limited to dozens of meters deep. Despite their tectonic origin, fracture-caves display a fairly good stability.

Smoky Cave

Mr. Meraklı indicated Smoky Cave entrance. It opens at the edge of the Kyrenia Crest (Fig. 1). The cave developed along an inclined opened fault, oriented N30°E, in recrystallized Triassic dolostone with subvertical dip. It is composed of two successive shafts, 16 and 10 m deep, respectively (Fig. 6). At the bottom of each shaft, the cave opening extends laterally along the fault, as large passages about 30 m long and 5 m wide. The cave is well decorated. In the first shaft, numerous curtains of speleothems have developed along the overhanging wall and were dry on the day of the visit (May 2018). Most of the stalagmites appeared inactive, corroded on the surface, and covered with brown crusts (Fig. 13A). On the contrary, in the Bottom Chamber, calcite formations are abundant, such as stalactites, stalagmites, and flowstones. They were wet and appeared active (Fig. 15A). A colony of bats (Pipistrellus pipistrellus) of several hundreds of individuals was present in a cupola of the deeper chamber. Guano is present as extended old dusty deposits at the bottom of the first shaft, and as fresh accumulations in the First Chamber and Bottom Chamber. A strong convective airflow exists at the entrance, with decreasing intensity at depth. The outflowing part of the loop made up of warm and wet air produces a plume of vapour when outside air is cooler (at night and in winter), hence its name “Smoky Cave”.

Pigeons Cave

Pigeons Cave opens on top of the crest of one of the easternmost reliefs of the Kyrenia range, 3.5 km east of Kantara castle (Fig. 7). The cave develops along an inclined opened fault, orientated N30°E, in recrystallized Permo-Carboniferous Kantara limestone cropping out as a blade limited on both sides by E-W transpressive faults. It is composed of two shafts of about 15 m each. At the bottom, the fracture extends on both sides as a passage of 1 to 2 m wide. Airflow is present in the northern side of the passage, showing a connection with the neighbouring surface.

CAVES IN THE MESSINIAN GYPSUM (TYPE [II])

Three gypsum caves have been studied in the area around Platania village, in the Famagusta district. The Messinian gypsum of the Kalavasos Formation corresponds to evaporite deposited in a marginal basin during the first
stage of the Messinian Salinity Crisis (MSC) (Fig. 2A). These deposits were exposed to erosion and karstification during the second major phase of the MSC, before being flooded and buried after the Pliocene transgression (Moccochain et al. 2012).

The gypsum strata, about 50 m thick, are located on the top of the Middle Miocene Kythrea Formation, which is composed of marls and sandstone flyschs (Harrison et al. 2008). The gypsum strata display several facies: the base is made up of an approximately 10 m thick layer of large selenite crystals, which breaks down as big boulders along the south slope. The rest of the strata is mainly made up of saccharoid gypsum. Close to the top of the plateau, a more calcitic-bedded layer, about 1 m thick, disaggregates as large and thin slates. The gypsum strata crops out as a monocline, with a gentle dip (≈15°) to the north. To the north of the area, at the foot of the Kyrenia range, the Kythrea Formation displays a strong dip, implying the probable presence of an important overthrusting (Fig. 2B). The area displays as an inclined plateau limited to the south by a 100 m high cliff above the Mesaoria Plain and cut by small valleys (Fig. 8). Two types of cave are present: i) caves on top of the cliff developing along a decompression fracture (First Day and Angry Bat caves); ii) paleo-spring cave (Fig Tree Cave).

Fig. 7: Pigeons Cave (at the feet of the group, in the circle), opens in Kantara permocarboniferous limestones bounded by E-W transpressive faults. View to the east, toward Karpas peninsula (Photo: P. Audra).

Fig. 8: Simplified sketch of the gypsum monocline cut by a perched dry valley. Fracture-caves open at the top of the crest. Fig Tree Cave opens a few meters above the dry valley.

Fig. 9: Entrance of First Day Cave, at the top of the southern gypsum cliff, looking at the Mesaoria Plain and Famagusta Bay in the distance. The cave develops along decompression fractures parallel to the cliff, which prepare the detachment of blocks. About 50 m below the crest, the gypsum rests on marls and sandstones of the Kythrea Formation (Photo: P. Audra).
First Day Cave

First Day Cave opens below the top of the cliff as a large entrance (6 m high; 4 m wide), prolonged by a 15 m long gallery (Figs. 9 & 10). At 10 m from the entrance, side passages are located on both sides. To the West, a 15 m long descending low passage harbours lateral rounded niches. To the East, a narrow and 5 m high and 15 m long ascending fracture rises up to a narrow passage plugged by collapsed blocks, close to the plateau surface. Both lateral passages develop along an open-fracture parallel to the cliff. A strong and cool (summer) airflow crosses the cave downward from the East passage to the entrance.

Angry Bat Cave

The entrance of Angry Bat Cave is similar to that of First Day Cave, 350 m to the East. The cave has developed along a decompression fracture, perpendicular to the cliff, as a 10 m high passage, 3 m wide at the entrance and narrowing to 0.5 m, and about 40 m in length (Fig. 11). The ceiling corresponds to the more calcitic-bedded layer that is not affected by the decompression fracture. Pigeons were nesting in the first part and Egyptian fruit bats (Rousettus aegyptiacus) observed in the inner part.

Fig Tree Cave

Fig Tree Cave (“İncirli Show Cave”) opens about 20 m above the floor of a perched dry valley crossing the gypsum plateau (Fig. 8). The cave displays a maze pattern along fractures, with a 5 m wide and 6 m high main passage at the entrance and smaller fracture-guided passages in the middle part, with a large Final Chamber (Fig. 12). Massive gypsum stalagmites are abundant. Air coming from the overlying plateau is flowing downward (in summer) toward the entrance. Bat guano is present, especially in the end-part, as extended thick (>0.5 m) dry deposits covering the floor.
METHODOLOGY

Some caves were previously mapped and studied by several groups (Jones & Rigby 1962; Jorgenson 1978; Satterfield 2015; Chirol & Savoi 2015, Spéléo-Club du Liban 2018). In addition to previously published data, we used a DistoX2 for additional cave survey combined with photographic documentation of morphological features. Climatic data were recorded using pSENSE RH portable CO\textsubscript{2} meter by Senseair, with an accuracy of ±0.6 °C for temperature, of 3% for RH < 90% and 5% for RH > 90%, and 30 ppm ±5% for CO\textsubscript{2} concentration. Radon concentration was measured in Fig Tree Cave during both the rainy and dry season (March and October 2017, respectively) using Sarad® DOSEman PRO dosimeter, with an accuracy of 150 cpm @ 1000 Bq/m³ (EEC). Guano and sediments mineralogy were identified by XRD at CINaM (CNRS and Aix-Marseille University), XRD patterns were recorded with Panalytical Xpert Pro, θ - θ geometry, Cu radiation (λ=0.15418 nm). ICDD-PDF2 database was used for phase identification. Three speleothems were sampled to constrain the age subsequent to the cave-opening phase. Two stalagmites were retrieved from Smoky Cave growing directly on the calcite flowstone sealing the cave floor. One stalagmite was sampled from Pentadactylos Cave at 50 m deep from the shaft entrance. Stalagmites were sampled from their base and the U-Th dating was conducted in Xi’an Jiaotong University, China (Tab. 4). Activity ratios were determined using a NU Plasma MC-ICP-MS following the procedure of Cheng et al. (2013).

RESULTS

SMOKY CAVE
The temperature was 17.7 °C at the bottom of the entrance shaft (May 2018) and 15.2 °C at the bottom of the cave (Dec. 2017 and May 2018), which differ by +1.4 °C and -1.1 °C from the local mean annual temperature (16.3 °C), respectively (Tab. 2). Relative humidity (RH) was 88.6% at the bottom of the first shaft, and 99.9% in the Bottom Chamber (May 2018). The first shaft appeared completely desiccated by entering dry air, whereas some places in the First Chamber ceiling showed discrete dripping originating from reliefs in massive rock with no apparent fissure, thus attributed to condensation. No seepage from surface was visible in May 2018. The Bottom Chamber was entirely wet, and moisture seemed to come entirely from condensation without seepage contribution during early-summer season.

Below the fresh guano deposits, where dripping provided moisture, calcite flowstones were tinted in dark brown, yellow and orange. DRX analysis of the brown crust covering the old corroded stalagmite of the first shaft (Fig. 13) indicated the presence of phosphate (hydroxylapatite), related to the mineralization of the neighbouring guano, associated to detrital components (quartz, illite), to some gypsum, and possibly to magnesian calcite (Fig. 13, Tab. 3). Possible phillipsite was detected; however, such zeolite mineral is unlikely in this environment, unless it is of detrital origin.

Some rounded features morphologies were identi-
Tab. 2: Climatic data measured in caves.

<table>
<thead>
<tr>
<th>Name of cave</th>
<th>Temperature (°C)</th>
<th>Relative humidity (RH, in %)</th>
<th>CO₂ (ppm)</th>
<th>Location of measurement</th>
<th>Month/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoky Cave</td>
<td>17.7 °C</td>
<td>88.6%</td>
<td>540</td>
<td>Bottom of entrance shaft</td>
<td>May 2018</td>
</tr>
<tr>
<td></td>
<td>15.2 °C</td>
<td>99.9%</td>
<td>600</td>
<td>Bottom Chamber</td>
<td>Dec. 2017</td>
</tr>
<tr>
<td></td>
<td>15.3 °C</td>
<td></td>
<td>689</td>
<td></td>
<td>May 2018</td>
</tr>
<tr>
<td>Pigeons Cave</td>
<td>17.8 °C</td>
<td>80.0%</td>
<td></td>
<td>Bottom</td>
<td>May 2018</td>
</tr>
<tr>
<td>First Day Cave</td>
<td>20.2 °C</td>
<td>67%</td>
<td>443</td>
<td>End of East lateral passage: strong and cool airflow, entering cave, descending from plateau surface</td>
<td>May 2018</td>
</tr>
<tr>
<td></td>
<td>32 °C</td>
<td>32%</td>
<td>440</td>
<td>Outside air</td>
<td>May 2018</td>
</tr>
<tr>
<td></td>
<td>17.7 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.8 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.1 °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.2 °C</td>
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<td>18.2 °C</td>
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<tr>
<td></td>
<td>18.1 °C</td>
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<td></td>
<td>18.0 °C</td>
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<td>18.3 °C</td>
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<tr>
<td></td>
<td>18.7 °C</td>
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<tr>
<td></td>
<td>18.1 °C</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>34 °C</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Tab. 3: DRX analysis results from samples of Smoky and Angry Bat caves (analysis CINaM).

<table>
<thead>
<tr>
<th>Cave</th>
<th>Sample no.</th>
<th>Disp.</th>
<th>Identified phases</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoky</td>
<td>Smoky</td>
<td>AT</td>
<td>Apatite, quartz, clay (illite) Probable gypsum</td>
<td>Surface of brown crust</td>
</tr>
<tr>
<td></td>
<td>Smoky_full</td>
<td>AT</td>
<td>Same as Smoky</td>
<td>Brown crust, including its light lower part</td>
</tr>
<tr>
<td>Angry_Bat</td>
<td>Yellow powder</td>
<td>Xpert</td>
<td>Gypsum, calcite, quartz, clay (illite or muscovite)</td>
<td>More calcite than gypsum</td>
</tr>
</tbody>
</table>

Tab. 4: ²³⁰Th dating results. The error is 2σ error. U decay constants: \( l_{238} = 1.55125 \times 10^{-10} \) (Jaffey et al. 1971) and \( l_{234} = 2.82206 \times 10^{-6} \) (Cheng et al. 2013). Th decay constant: \( l_{230} = 9.1705 \times 10^{-6} \) (Cheng et al. 2013). ** \( \delta_{234}^{U*} \) was calculated based on \( \delta_{234}^{U*} \) initial was calculated based on \( \delta_{234}^{U} \) measured \( \times e^{237X_{t}} \). Corrected \( \delta_{234}^{U} \) are the values for a material at secular equilibrium, with the bulk earth \( 230\text{Th}/238\text{U} \) value of 4.4 ± 2.2 e. Those are the values for a material at secular equilibrium, with the bulk earth \( 230\text{Th}/238\text{U} \) value of 3.8. The errors are arbitrarily assumed to be 50%. ***B.P. stands for “Before Present” where the “Present” is defined as the year 1950 A.D.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>( ^{238}\text{U} ) (ppb)</th>
<th>( ^{232}\text{Th} ) (ppt)</th>
<th>( ^{230}\text{Th}/^{232}\text{Th} ) (atomic x10⁻⁶)</th>
<th>( \delta_{234}^{U*} ) (measured)</th>
<th>( \delta_{234}^{U*} ) (activity)</th>
<th>( ^{230}\text{Th} ) Age (yr.) (uncorrected)</th>
<th>( ^{230}\text{Th} ) Age (yr.) (corrected)</th>
<th>( \delta_{234}^{U*} ) initial (corrected)</th>
<th>( ^{230}\text{Th} ) Age (yr. BP) (corrected)</th>
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<tr>
<td>SMOKY1-00</td>
<td>552.8 ±0.8</td>
<td>994 ±20</td>
<td>3,263 ±66</td>
<td>18.0 ±1.4</td>
<td>0.3560 ±0.0008</td>
<td>46,856 ±159</td>
<td>46,804 ±163</td>
<td>21 ±2</td>
<td>46,736 ±163</td>
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<tr>
<td>SMOKY2-01</td>
<td>336.0 ±0.5</td>
<td>797 ±16</td>
<td>2,438 ±49</td>
<td>12.9 ±1.5</td>
<td>0.3507 ±0.0008</td>
<td>46,301 ±155</td>
<td>46,233 ±162</td>
<td>15 ±2</td>
<td>46,165 ±162</td>
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<td>Pentad00</td>
<td>109.0 ±0.1</td>
<td>167 ±4</td>
<td>10,485 ±224</td>
<td>181.6 ±1.2</td>
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<td>174,720 ±751</td>
<td>174,685 ±751</td>
<td>297 ±2</td>
<td>174,617 ±751</td>
</tr>
</tbody>
</table>
fied. In the first shaft, the ceiling had a half-cylindrical channel connected to the entrance that gradually disappeared inwards (Fig. 6). The surface of the ceiling channel was smooth, with no sign of calcite deposits. The curtains covering the overhanging wall appeared to be fed by runoff originating from this ceiling channel. However, the host rock of this ceiling channel was extremely massive and did not present any evidence of seepage from the surface through fissures. In addition, at the end of the First Chamber, a 1.5 m wide channel rose along the overhanging wall toward the top of the fracture. Here, fresh guano was also present along the wall. In the same place, the wall locally consisted of fault breccia, where cement was deeply corroded but angular elements stood in relief. A calcite popcorn line delimited this deeply corroded zone (Fig. 14). No fluvial deposits and no marks of concentrated flow were present.

The active stalagmites of the wet Bottom Chamber displayed typical facies, made of thick layers of white lamina alternating with thinner layers of dark brown lamina (Fig. 15B). A discrete corrosive dripping had weathered and disaggregated a block of dolostone in the deepest part of the shaft (Fig. 16).
THE CONTRIBUTION OF CONDENSATION-CORROSION IN THE MORPHOLOGICAL EVOLUTION OF CAVES IN SEMI-ARID REGIONS: PRELIMINARY INVESTIGATIONS IN THE KYRENIA RANGE, CYPRUS

PIGEONS CAVE
The cave temperature was 17.8 °C (May 2018) and lower (-0.3 °C) than the local mean annual temperature (Tab. 2). The RH was 80.0% (May 2018) inside the cave, which was entirely dry. Some massive stalagmites and corroded flowstones were present at the bottom (Fig. 17). The floor was covered by a thick (0.5–1 m) layer of pigeon guano. No fluvial morphologies and related deposits were observed in this cave.

FIRST DAY CAVE
A strong and cool airflow (20.2 °C; 67% RH) was entering the cave from the end of the East lateral passage, descending from the plateau surface, in May 2018 (Tab. 2). Such important airflow is driven by the high temperature gradient. The main gallery and the West gallery displayed round morphologies (cupolas, round blind ends, arches, lateral niches) that covered all walls and ceilings (Fig. 18). The East fractures showed smooth walls and ceiling channels similar to a vadose meander. In the entire cave, a constant vertical distribution of features was observed: the ceiling and the upper part were smooth and exposed with no crust features. However, in the lower part of the cave section, a gypsum crust with nodular morphology gradually appeared and thickened downwards with more than 10 cm thickness. In the West gallery, the ceiling cupolas intersected as round reliefs that collect the runoff from cupolas and produced small stalactites and their correspondence on the floor. Some open-fractures, parallel to the cliff, intercepted the cave walls of the main gallery and displayed some gypsum rims (Fig. 19). No fluvial morphologies and deposits were observed inside the cave.

ANGRY BAT CAVE
The ceiling was carved by a slightly rounded channel. Together with the upper part of the passage, the cave wall was exposed, smooth and showing corrosion processes. The lower part of the cave wall, however, was covered by gypsum crust, thickening downwards (Fig. 11). A thin (1 cm) layer of yellowish dry powdery crys-
DIDIER CAILHOL, PHILIPPE AUDRA, CAROLE NEHME, FADI HENRI NADER, MLADEN GARAŠIĆ, VASILE HERESANU, SALIH GUCEL, IRIS CHARALAMBIDOU, LAUREN SATTERFIELD, HAI CHENG & R. LAWRENCE EDWARDS

tals was inserted between the hard gypsum crust and the gypsum wall. DRX showed the presence of mainly calcite, then gypsum, with trace of detrital minerals (quartz and illite-muscovite). The wall surface displayed gypsum macrocrystals that were vertically cut with sharp edges showing a levelled corrosion below the crust. Bat guano covered the floor of the inner fracture passage. No fluvial morphologies or deposits were detected inside the cave.

FIG TREE CAVE
Passage profiles showed exposed and smooth channels on the ceiling and lateral notches with a flat roof at the entrance (Fig. 21). The notches developed at the same level, which also corresponded to the original level of the entrance (Fig. 12), before being partly constricted by collapsed blocks. Since the cave is located at the outlet of a valley crossing the gypsum plateau toward the Mesaoria Plain, the notches and the ceiling channels indicate an old outflow draining the gypsum aquifer.

A 5 m deep slot was visible at the end of the entrance gallery (Fig. 21C) with a patch of scallops at the bottom. It probably acted as a feeder during the phreatic stage, from which the water was rising from the depth to the main level. At the end of the cave, another slot probably acted in a similar way (Fig. 12). Moreover, in the end part, a passage was completely filled with fluvial sediments. They consisted of laminated yellowish-greenish silts, made up of 75% of carbonate and 25% of microcrystalline gypsum grains. The laminated cave deposits gradually fell apart in the gallery, exhuming the previously covered walls and showing sharp and levelled

![Fig. 20: Angry Bat Cave. A) View toward the ceiling, about 1 m in width (Photo: D. Cailhol). B) View along the inner fracture (person for scale in the circle). Ceiling and upper parts of the wall are exposed, smoothed by condensation-corrosion along the cooler ceiling, while lower part of the wall shows a gypsum crust thickening downwards by evaporation due to drier air at the bottom (Photo: D. Cailhol).](image)

![Fig. 21: Fig Tree Cave, phreatic features from the initial active phase. A-B) Ceiling channels from the early phreatic phase are located above lateral notches from a subsequent epiphreatic phase after partial de-watering (Photos: D. Cailhol). C) Downward view of the 5 m deep slot, probably a feeder from which water was flowing up (Photo: D. Cailhol).](image)

![Fig. 22: Fig Tree Cave, condensation-corrosion features of the late phase. A) Round blind termination, with typical profile showing round ceiling channel with exposed rock where condensation-corrosion occurs on cooler ceiling, and lower walls covered by downwards thickening crusts of gypsum made by evaporation (Photo: D. Cailhol). B) Boulder choke in the final chamber, showing blocks with sharp edges in the collapse, whereas fallen blocks on the ground have been rounded and smoothed by condensation-corrosion (Photo: D. Cailhol).](image)
The contribution of condensation-corrosion in the morphological evolution of caves in semi-arid regions: preliminary investigations in the Kyrenia Range, Cyprus

Gypsum crystals with a uniform corrosion at the contact of the deposit. These fine sediments also witnessed an old phreatic phase, transporting material from the aquifer itself.

Some passages end with rounded morphology (Fig. 22). Classical vertical distribution of features occurred, with exposed ceiling and upper walls, whereas the lower parts of the walls were covered by gypsum crust, thickening downwards (Fig. 22A) and decorated by abundant stalagmites. In the Final Chamber, a side passage was blocked by a collapse of angular blocks. The fallen blocks were rounded with no sharp edges (Fig. 22B). In the last passage leading to the end-part of the cave, two parallel rims joined to form a central sidewalk (Fig. 23). At the end of the entrance gallery, condensation runoff collected at the lower edge of the ceiling channel, creating a small stalactite that produced a drip hole in the gypsum ground.

The cave temperature (May 2018) ranged between $17.7^\circ C$ in the end-part of the cave and $18.7^\circ C$ along the ceiling at the entrance part. The RH inside the cave was around 80–90% at the cave floor and reached 95–100% along the cave ceiling (Tab. 2). It showed the possibility of condensation on the ceiling and evaporation on the floor.

A high concentration of $SO_2$ was detected near the cave floor (1 m above the floor). The $CO_2$ concentration was around 530 ppm along the cave floor and 1000 ppm along the ceiling. $^{222}Rn$ concentration, measured in the slot at the end-part ($\approx$200 m from entrance; 13 m depth), displayed values between 22,000 and 30,000 Bq/m$^3$/s (Tab. 5).

**DISCUSSION**

We discuss the main results obtained regarding the morphological features of each cave as an expression of cave genesis, the relief evolution mainly resulting from tectonic history, the condensation-corrosion as a major late stage evolution process, and the effect of bat guano as a booster of the condensation-corrosion process.

MORPHOLOGICAL FEATURES AS AN EXPRESSION OF CAVE GENESIS

**Smoky Cave**

Since no initial fluvial stage occurred and since it is located on a crest with a negligible catchment above the
cave, the rounded morphologies are obviously linked to condensation-corrosion. In warm periods, stable conditions with no significant airflow gradually lead to the equilibrium of the inner temperature. However, in cold periods, instability produces cold air inflow.

In the first shaft, convective airflow raises, cools, and canalizes along the ceiling toward the entrance, making condensation and eventually corroding the rounded ceiling channel (Fig. 6). Since the ceiling channel is carved into massive recrystallized carbonates, where few fissures are visible and seepage could only occur during winter season, most of the water during late-spring and summer seasons is expected to come from condensation only (Frumkin et al. 2018). Therefore, the curtains along the overhanging wall would mainly be fed by moisture originating from the ceiling channel. The condensed water gradually saturates and evaporates while flowing (Bradley 2015). In the First Chamber, convection loops make local condensation-corrosion that carves the rising channel located at the end of the chamber and on the breccia zone. Due to the complex distribution of convective loops, this corroded breccia is surrounded by an evaporation zone delimited by a popcorn line (Frumkin et al. 2018). This results in evaporation of the moisture from the condensation zone (Fig. 14). Discrete drippings on guano deposits make colorful calcite flowstones. In the Bottom Chamber, the permanent moisture cannot be related to the epikarst seepage, especially in the dry season. This moisture would result from the presence of the bat colony releasing vapour, together with heat and CO₂, which are distributed by the local convection cells (Lundberg & McFarlane 2009, 2012, 2015; Frumkin et al. 2018). Moreover, the mineralization of guano releases acids (carbonic, nitric, phosphoric, and sulphuric) that strongly contribute to the aggressiveness of condensation water. Bat metabolism and guano mineralization are clearly responsible for the weathering of the blocks below the dripping points (Fig. 16), for the development of convection cupolas used as roost places, for the ceiling channels (Audra et al. 2018), and probably also for the active speleothems that are densely developed in this chamber (Fig. 15A).

Pigeons Cave
Similarly, it is located on a crest that excludes any initial fluvial stage, which is confirmed by the absence of characteristic morphologies and sediments. Consequently, the corrosion of the flowstone (Fig. 17) could only have occurred through condensation water, with its aggressiveness boosted by the mineralization of pigeon guano (Shahack-Gross et al. 2004). Since the cave is dry in the hot season, such condensation may prevail in the winter season, where cave air instability allows strong convec-

itions, with sinking of outer cold air and rising of the corresponding cooling warm air.

First Day Cave
It harbours a set of rounded features (cupolas, ceiling channels, niches) that cover the entire walls and ceilings (Fig. 18). Since no fluvial sediments or morphologies are present and since a past activity as outflow cave in unlikely, such rounded features clearly point toward a condensation-corrosion process. It occurs on the cooler ceiling and inside opened fractures, whereas evaporation and deposition of thick crusts occur close to the warmer and drier ground and at the rim of decompression fractures (Fig. 19; Gázquez et al. 2015). Such processes must mainly occur during winter, when cold air entering the main gallery along the floor returns outside while cooling along the ceiling. First Day Cave seems to be entirely enlarged by condensation-corrosion starting from opened-fractures. The option that this cave could be a relic of an old perched fluvial outlet cannot be ruled out, but it is unlikely since no evidence points toward such an origin. In the probable case of a condensation-corrosion enlargement, the resulting size of the passages (up to 4 m diameter) is significant.

Angry Bat Cave
For the same reasons, all smooth phreatic-like morphologies (slightly rounded channel, exposed upper walls) clearly result from condensation-corrosion processes and in turn from evaporation for the gypsum crust covering the lower walls. Here, the soft material sandwiched between the corroded wall and the gypsum crust, made of powdery crystals of calcite and gypsum could come either from the disaggregation of the more carbonated ceiling or from the crystallization of calcite by common-ion effect in sulphate-saturated solution, or from both. The presence of quartz and clay points toward at least a partial contribution of detrital component.

Fig Tree Cave
The cave clearly acted as a discharge point, as shown by lateral epiphreatic notches that are connected to the level of the entrance (Figs. 12 & 21). Ceiling channels, located 1–2 m above, could correspond to an early phreatic phase before the partial dewatering. The water had probably risen from the slot, acting as a feeder, as shown by the wall features that probably correspond to scallops. Additional feeders from the inner fractures are likely. These feeders drained the gypsum aquifer at a shallow depth, since the underlying flysch aquiclude is located only 10–15 m below the cave passages. The fine sediment filling the end-part is linked to this early active phase, probably related to the incision of the valley during the Late Pleis-
tocene. However, the re-activation of an intra-messinian paleokarst, filled during the Pliocene transgression, cannot be ruled out (Mocochain et al. 2012). In a later phase, after a base-level lowering and water draining of the cave, airflow crosses the cave, making condensation-corrosion by cooling of warm air on the ceiling, and evaporation-deposition by warming of air flowing along the floor. Condensation-corrosion on the ceiling maintains an exposed and smooth rock surface, while evaporation along the floor favours the deposition of gypsum crusts (Fig. 22) and the upward development of rims that eventually join as a central sidewalk (Fig. 23).

MORPHO-TECTONIC EVOLUTION
The landscape evolution of the northern part of Cyprus is recent, consecutive to the emersion of the Kyrenia Range starting in the Early Pleistocene (Palamakumbura et al. 2016). Indeed, the Kyrenia Range emersion is subsequent to the uplift of the coastal mountain ranges in Lebanon and Syria that emerged earlier during the Oligocene (Nader 2011) and later during the Plio-Pleistocene. The karstification phase of the Kyrenia Range is therefore recent, resulting in the development of vertical fractures with no marked cave levels, whereas the karstification phases of the coastal Levantine Range resulted in several marked multi-level karst systems (Nehme et al. 2016).

As for the gypsum outcrops of the Mesoaria Plain, the evolution of the studied caves could have briefly occurred during the MSC (Mocochain et al. 2012), before its definitive emersion in the Pleistocene and therefore be considered older than the caves in Kyrenia Range.

Fracture-caves of the Kyrenia Range carbonates
Their origin obviously postdates the emersion of the Kyrenia Range in the Early Pleistocene. Caves in lower altitudes are obviously much more recent due to the later emersion. Caves at higher altitude could be of any age in this period, according to the successive tectonic phases. The U/Th dating applied on cave calcite give a minimal age to the cave evolution of Kyrenia. Three speleothems collected from Smoky and Pentadactylos caves (Tab. 4) showed ages at 46.7±0.16, 46.1±0.16, and 174.6±0.76 ka BP at their basal section, inducing a fracture opening phase prior to the end of the Middle Pleistocene period.

The fracture-caves are linked to the permanent activity of the transpressive faults that opened the N30°E conjugate pull-apart fractures. Eventually, they evolved by local collapses, probably in relation to seismic activity. Surprisingly, decompression fractures do not significantly affect caves, even near cliffs and steep slopes, which appear to remain relatively stable. Flowstones development occurred, especially during the wetter periods. Condensation-corrosion is at the origin of ceiling channels and the correlated evaporation-deposition produces popcorn lines (Smoky Cave). As a result, caves often display a geometric aspect with sharp walls and succession of shafts or chambers developed along the inclined faults, separated by constrictions due to rock fall accumulations. The floor consists of large collapsed blocks. Speleothems partly cover the walls and the floor. Only ceiling channels and some speleothems show intense but focused corrosion made by condensation from convective airflows, hence their similarity to phreatic morphologies, also carved by turbulent flow.

Caves in messinian gypsum
Two types of cave occur. The first type corresponds to caves located on top of the cliff, which originate from decompression fractures. Airflow at the origin of condensation-corrosion dramatically enlarged the initial narrow fractures, producing on top of walls and ceilings rounded features such as ceiling channels, cupolas, and wall niches. It eventually achieves wide phreatic-like morphologies (First day Cave), even though there had no initial fluvial phase. In the lower part of walls, evaporation makes thick gypsum crust. The second type corresponds to discharge caves (Fig Tree Cave). In the initial phreatic phase, water was rising from a shallow depth through feeders along fractures connected to a maze controlled by the fracture network, then converging to a main trunk. It eventually discharged at the current cave entrance acting as a spring in the valley. A moderate base-level lowering allows a partial dewatering of the cave and the development of epiphreatic wall notches. The late phase occurred after the draining of the cave when the valley became perched and abandoned. Airflow crossing the cave produced condensation-corrosion with exposed rock along ceiling channels. In the lower part of passages, warm and dry air allowing evaporation makes thick gypsum crusts and abundant gypsum stalagmites.

Finally, the microclimate of this cave shows very high concentrations of radon and sulphur dioxide. The detection of SO$_2$ is not frequent in caves. Apart from volcanic caves, very few cases are reported in the literature, such as in the caves of Acquasanta Terme, Italy (Galdenzi 2017) and in Cueva de Villa Luz, Mexico (Hose et al. 2000). In the last case, the high SO$_2$ concentration (>35 ppm), associated to high levels of CO$_2$ and H$_2$S, would have its origin in evaporites buried at depth in Tabasco oil fields and in the possibility of fast transfer to the surface along major fault lines. In Fig Tree Cave, the SO$_2$ gas could be related to the bacterial reduction of sulphates from the gypsum into sulphur, which in turn oxidizes in SO$_2$. The dry environment with the absence of water would possibly limit the oxidation into sulfuric acid, favouring SO$_2$ production by direct oxidation of the sulphur in the
presence of air, as already observed by the authors (DC, PA) in Grotta Aqua Mintina, a very dry gypsum cave in Sicily, Italy. Another possibility would point toward a deep crustal origin associated to the proximity of major transpressive active faults. The $^{222}\text{Rn}$ concentrations measured in Fig Tree Cave were very high, about two orders of magnitude higher than the usual values measured in caves (Field 2007). Lower values were recorded at the end of the dry season, whereas higher values correspond to the rainy season and to a period of tectonic activity in the northeastern part of the island. Surprisingly, CO$_2$ concentration remains in the normal range. Accordingly, the high concentrations of sulphur dioxide and radon could possibly be related to deep-seated fluids originating from the neighbouring transpressive fault activity, or, for the SO$_3$ only, to sulphate redox in very dry conditions.

Because of high solution rates, gypsum karst is known for its fast changes. However, the semi-arid climate of Cyprus must slow down its evolution. Decompression caves are clearly connected to the current retreat of the cliff, which however appears to be moderate. The discharge Fig Tree Cave developed in relation to the evolution of the valley, which is now perched and abandoned. The age of the caves is still unknown, but their close connection to the recent landscape would suggest a Late Pleistocene age.

CONDENSATION-CORROSION AS MAJOR LATE STAGE PROCESS IN SEMI-ARID CLIMATE

In addition to the common processes of cave evolution, such as block collapse and speleothems deposition, condensation-corrosion acts as a major process in the late stage of cave evolution. Condensation-corrosion is at the origin of rounded and smooth features (ceiling channels, corroded speleothems, and focused zones of rock wall corrosion). Due to the similar behaviour of airflow fluid, such features resemble phreatic morphologies, making it difficult to identify their true origin in most of the caves. In the studied fracture-caves of Cyprus apart Fig Tree Cave, in both carbonate and gypsum, where no initial phreatic phase has occurred, these rounded features located only in the upper part of the passages must be assigned to condensation-corrosion only. Such characteristic of Cyprus fracture-caves is fundamental for studying the role of condensation-corrosion and its extent. In such a dry environment, condensation may also be at the origin of moisture. After the wall corrosion and gradual saturation, produced water flows along walls and produces calcite precipitation such as the curtains of Smoky Cave. Due to the apparent absence of dripping from epi-karst seepage through the massive recrystallized carbonate rock, some of the speleothem’s late evolution could be related to condensation-corrosion (Frumkin et al. 2018).

The correlative process of condensation-corrosion by cooling airflow occurring from convection cells is the evaporation of sinking cool air that warms along the cave bottom. In carbonate caves, evaporation favours the precipitation of calcite popcorns around wet zones. In gypsum caves, it is at the origin of massive gypsum stalagmites and thick gypsum crusts covering the lower part of walls. Sidewalk rims, made by the coalescence of upwardly growing rims, are uncommon features.

Condensation-corrosion activity follows a seasonal trend. In summer, descending caves with only one entrance have a stable atmosphere. Colder cave air is trapped and exchanges are limited to barometric changes and wind pulses that can push air in and out. On the contrary, in winter, the unstable cave atmosphere allows cold surface air to enter the caves, triggering powerful convections that blow out inner warm air. This latter condenses while cooling and produces a cloud outside the cave by mixing with cold atmospheric air, hence the name of Smoky Cave (Fig. 6). Cold inflowing air is gradually warmed at the contact of the rock, which is warmer, and probably by the presence of the bat colony that release heat and vapour. Such winter inflow of cold air also explains why its bottom temperature is more than 1°C lower than the mean local temperature at this altitude, due to a dominant effect of surface temperature during winter, typical of such “cold traps”. This is the case of many fracture-caves in carbonate rocks. Caves with two entrances located at different altitudes are almost permanently ventilated by the chimney effect, with ascending airflow in winter (cave air warmer than outside) and descending airflow in summer (cave air cooler than outside). Inner temperature is thus influenced at the proximity of the inflowing entrance: in May 2018, Fig Tree Cave temperature was 1.4°C lower than the surface average, due to previous cooling by strong air flow entering during the previous winter (Fig. 12); on the contrary, First Day Cave, which is close to the engulfing entrance, was already 0.8°C warmer in May than the surface average. Pigeons Cave is a mixed case, acting as a cold trap in winter combined to ventilation with another entrance, providing a temperature of only 0.3°C lower than the surface average. Such a dynamic is important, since rock wall cooling in winter increases the temperature gradient and thus condensation volume. On the contrary, in summer, hot (35–45°C) and dry external air (RH < 30%) entering in fresh caves is not sufficient to reach the dew point, even by a cooling of up to 10–15°C: caves remain dried by airflow. Such seasonal dynamic was previously noticed in Sorbas caves, South Spain, which has a climate similar to Cyprus, where condensation mainly occurs in winter (Gázquez et al. 2017). Isotope ratios have also shown that the solution at the origin of gypsum crusts
and speleothems is made of 60% of condensation water and the rest of seepage water. Consequently, in Cyprus, the peak of condensation probably occurs in winter, in both gypsum and carbonate caves.

The volume of the corroded rock by condensation-corrosion is difficult to quantify. Long cave climatic data, including temperature, RH, and pCO$_2$, are missing and insufficient for such quantification. Extrapolation to any rock volume corrosion would assume a constant rate, which is obviously not the case. The morphological connection between the cave and the surface, allowing significant air exchange, is also a key point. However, for First Day cave, using the rates of wall retreat (3.3 cm/ka) calculated for Sorbas caves (Gázquez $et$ $al.$ 2015) that develop in a similar climate, an estimation of its development would require about 100–200 ka, assuming constant rates of wall retreat.

**ROLE OF BAT COLONIES AND GUANO DEPOSITS**

The presence of bat colonies is recognized as an important factor for increasing corrosion, especially when it occurs from condensation (Lundberg & McFarlane 2009, 2012, 2015; Frumkin $et$ $al.$ 2018; Audra $et$ $al.$ 2016 and reference therein). Bats contribute to cave climate change by their metabolism and their breath, providing significant amounts of heat, vapour, and CO$_2$. The mineralization of guano accumulations also provides heat, combined with acid production (carbonic, phosphoric, sulfuric, and nitric). Not only the floor is carved by guano acids, but also convection cupolas develop very fast by condensation boosted in such acidic environments, together with ceiling channels, wall retreat, corrosion of flowstones, etc. We assume that pigeon guano can have a comparable effect, but probably more limited, since grain-feeding animals provide less aggressive catabolic byproducts (Shahack-Gross $et$ $al.$ 2004).

Since no seepage from epikarst occurs in the dry season in Smoky Cave, the presence of a bat colony in the semi-confined Bottom Chamber could probably be at the origin of the permanent moisture. The activity of speleothems, which is permanent only in this area, could also be related to bat moisture. Similarly, alternating white and brown laminae have been observed in some speleothems from Smoky Cave. The origin of the brown color is still unknown. It could originate either from soil organic infiltration and precipitation or from guano byproducts and in that case could record the temporary presence of bats.

Finally, such bat-related acidic sources are not active in gypsum caves, since the solubility of this mineral is not significantly influenced by acidity. In gypsum caves, even if bats are present, only the condensation volume can explain the development of the observed corrosion features.

**CONCLUSION**

- Two types of caves were studied in Cyprus: firstly, fracture-caves in the Kyrenia Range carbonates as pull-apart open-voids derived from the transpressive fault activity, and as decompression fractures on top of gypsum cliffs; secondly one discharge cave in gypsum as fracture-guided mazes fed by deep feeders.
- Late stage of cave evolution was governed by condensation-corrosion, after opening to the surface with air exchanges and potentially colonization by bats (Fig. 24).
- The advantage of fracture-caves is that most of them had never undergone the usual initial phreatic flow, so that discrimination with phreatic morphologies, which is generally equivocal in other areas, is not questionable here. Condensation-corrosion is the only process able to carve rounded morphologies made by convective airflows. Consequently, rounded morphologies (ceiling channel, cupolas, wall niches, and corroded flowstones) are made by airflow convections driving condensation-corrosion processes (Fig. 24).
- The correlative evaporation produces popcorn lines in carbonate caves; in gypsum caves it produces thick gypsum crusts, massive gypsum stalagnites, and sidewall rims, which are uncommon features.
- Since in summer inflowing air is too dry to provide significant moisture in such a semi-arid climate, it seems that most of the condensation occurs in winter, when the instability of the cave atmosphere allows renewed of the inner cave air in both “cold trap caves” and caves where air is flowing between two entrances.
- Some gypsum fracture-cave enlargement through condensation-corrosion could reach up to 4–5 m width, that would require about 100–200 ka, according to wall retreat rates obtained in Southern Spain.
- Bat colonies significantly increase the aggressiveness of condensation-corrosion in carbonate caves, providing permanent moisture, vapour, heat, CO$_2$, and guano that releases heat and acids. Pigeon guano possibly has a similar effect, although probably less efficient.
- Caves are recent, and developed with the uplift of the
Kyrenia Range during the Pleistocene, and especially during the Late Pleistocene for gypsum caves.

- High concentrations of $\text{SO}_2$ and $^{222}\text{Rn}$ detected in Fig Tree gypsum cave could be partly related to the activity of the neighbouring transpressive fault.

Although they seem inactive and dry, the studied Cypriot caves are still currently evolving under the condensation-corrosion process. Even with no flowing water and very limited dripping, the speleogenetic process is still fully active and produces ongoing corrosion morphologies and speleothems in caves that have a relict appearance.

Future research should integrate ongoing cave climate monitoring in Smoky and Fig Tree caves, to better assess and quantify air exchanges and condensation-corrosion processes. First U/Th dating of stalagmites in Smoky Cave provided a minimal age for the opening of fracture caves and a chronological frame for the development of the condensation-corrosion morphologies in this cave. High-resolution isotopic data would help to better figure out the part of seepage and condensation on speleothems building in such environment. Finally, measurements of $\text{SO}_2$ and radon concentrations, together with sulphur isotopes in Fig Tree Cave could confirm a deep-seated origin for gas released from the current activity of the nearby transpressive fault.

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