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Hypogenic speleogenesis, late stage epigenic overprinting and condensation-corrosion in a complex cave system in relation to landscape evolution (Toirano, Liguria, Italy)

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Hypogenic speleogenesis, late stage epigenic overprinting and condensation-corrosion in a
complex cave system in relation to landscape evolution (Toirano, Liguria, Italy)
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29

30 Abstract

31 The Toirano karst system is located in the Ligurian Alps (north Italy), around 4.5 km inland from 32 the coastline and carved in Middle Triassic dolostone. It comprises five cave levels over a 154 m 33 altitudinal range, specifically Ulivo (340 m a.s.l.), Colombo (247 m a.s.l), Upper Santa Lucia (215 34 m a.s.l.), Lower Santa Lucia (201 m a.s.l.) and Bàsura (186 m a.s.l.) caves. The system is active at 35 lower altitudes, as testified by the thermal spring currently located at 70 m a.s.l. along the Varatella 36 valley. Speleogenesis was attributed to the action of epigenic processes by other authors. However, 37 the extraordinary geodiversity of the underground morphologies and deposits are at odds with this 38 interpretation. Accordingly, this work investigates the genesis of the Toirano karst system, in 39 relation to the landscape evolution of the surrounding area. A detailed morphological and 40 mineralogical investigation of cave geoforms and deposits, together with the presence of an active 41 low thermal sulphide spring on the Varatella valley and only ~100 m below the Bàsura Cave, 42 sustain the hypothesis of a hypogene origin of the caves. This work shows that most of the caves 43 formed close to the former water table (base) level, in turn determined by the mean sea level. 44 Geochronological analyses, including U/Th (n = 13) and cosmogenic burial (n = 1) dating, together with an estimated incision rate of the Varatella valley of around 0.1 mm y^{-1} , have allowed to assess 45 46 the age of the highest cave (Ulivo) at around 2.7 Ma, Colombo at ~1.8 Ma, Upper Santa Lucia at ~1.5 Ma, Lower Santa Lucia ~1.3 Ma and Bàsura at ~1.2 Ma. Estimated palaeotemperature attained 47 48 through isotope analyses and fluid inclusions on speleothems suggest that the temperature of rising 49 waters was lower than 50 °C and possibly ranging between ~12 and ~20°C, indicating that 50 hydrothermal fluids were not the main driver of speleogenesis, at least in the late speleogenic 51 phases. Additionally, sulphuric acid speleogenesis by-products were not identified. Accordingly, 52 hypogenic speleogenesis occurred because of the action of low temperature CO₂-rich rising fluids.

A late stage of epigenic speleogenesis has been detected because of the clear evidences of condensation-corrosion morphologies, occurred since ~150 ka (possibly earlier) when caves were finally connected to the surface because of valley enlargement. Besides uncovering the genesis of the Toirano karst system, this study demonstrates that the combination of local geology, surface vs underground geomorphological observations, climate change vs landscape evolution evaluation and geochemical data is of key importance for interpreting subsurface land-shaping processes.

59

60 Keywords

61 Speleogenesis, hypogene karst, dating, stable isotopes, cave geomorphology

62

63 1. Introduction

64 The geological non-specialist community, as well as the public, is often unaware of the multiple 65 processes leading to cave formation. Indeed, speleogenesis is too often considered as an epigenic 66 process (sensu Ford and Williams, 2007) only. In this circumstance, the hydrogeological circulation 67 ultimately leading to cave excavation is sustained by surface water infiltrating the bedrock. The 68 action of bedrock dissolution in phreatic, epiphreatic, and vadose conditions along the water table is 69 also often taken for granted. Indeed, epigene caves are often arranged in levels, which record the 70 former base level (water table) stillstands (Palmer, 1987), and can thus help in unravelling the 71 landscape evolution of the areas in which they were carved (Calvet et al., 2015; Columbu et al., 72 2015, 2017; Bella et al., 2019; Ballesteros et al., 2019; Pennos et al., 2019; Nehme et al., 2020). 73 However, cave formation does not exclusively occur through epigenic speleogenesis. An increasing 74 body of evidence suggests that many caves formed by hypogene processes (sensu Klimchouk, 75 2007), which imply upward recharge from a deep route rather than epigenic input (Plan et al., 2012; 76 Tisato et al., 2012; Klimchouk et al., 2017; Pérez-Mejías et al., 2019; Klanica et al., 2020). Rising 77 fluids are rich in CO₂ and/or H₂S, and can be sourced from deep hydrothermal activity (Temovski et 78 al., 2013). Hypogene caves can also form at former water table levels, such as in the case of thermal caves (Léel-Őssy, 2017), and particularly in sulphuric acid (SAS) caves, where degassing of H₂S
and oxidation is most efficient at or immediately above the water surface (De Waele et al., 2016;
D'Angeli et al., 2019a). Hypogene-SAS caves are reliable indicators of past water table levels and
can help in determining base level changes, and especially uplift rates (or related downcutting rates
in adjacent valleys) (Piccini et al., 2015; De Waele et al., 2016; D'Angeli et al., 2019b).

84 The common epigenic origin is usually supported by the current presence of water streams in caves 85 and/or the "rounded" passages interpreted as phreatic conduits (Sauro et al., 2020). However, the 86 modern streams and the actual shape of natural underground conduits can be the result of recent 87 geological events; the effective processes leading to cave formation must be traced further in the 88 past, i.e. when the initial fluids started enlarging the most permeable pathways, leading to the 89 selection of the most effective drainage routes (Ford and Williams, 2007; Palmer, 2007). 90 Furthermore, the geomorphological evidences of ancient speleogenesis can be partially lost because 91 of weathering, speleothem deposition, sedimentation, collapses, human activity, etc. (Sauro et al., 92 2019). There are processes such as condensation-corrosion, boosted by the presence of guano 93 and/or warm and moist air circulation in caves, which are greatly underestimated in the shaping of 94 caves (Audra et al., 2016; Cailhol et al., 2019; Dandurand et al., 2019). These processes, instead, 95 can be extremely important in the late speleogenetic stages, especially when cave passages become 96 largely opened to the surface, concurrently erasing evidences coming from the deeper past. 97 Accordingly, the study of cave formation needs an accurate interpretation of underground 98 morphologies (conduit shape, size, geometries; wall, ceiling and floor features; chemical 99 precipitates and sediments; etc.), which should also be supported by geochemical and stratigraphic 100 analyses of cave deposits (speleothems vs. sediments), considerations about the bedrock 101 discontinuities (faults, lineaments, bedding, etc.), the geological status of the area (active tectonic, 102 uplifting vs. subsidence, etc.), and evaluations about surface dynamics related to climate and 103 landscape evolution (De Waele et al., 2009; Audra and Palmer, 2015; Columbu et al., 2015, 2017).

Additionally, speleogenetic processes must be pinpointed in time, thus dating is a key for anchoring
underground processes to a coherent geochronology (Sasowsky, 1998).

106 The Toirano karst system in Liguria, Northern Italy, is developed along a series of close-to-107 horizontal cave passages and an impressive variety of underground morphologies, as much as 108 probably making it the Italian show cave with the highest geodiversity. Its features challenge a 109 straightforward interpretation of its formation, although past local investigators have considered 110 epigene speleogenesis as the main player. However, the presence of a nearby thermo-mineral spring 111 suggests a possible influence of a deep flow component, and substantial differences in 112 morphologies are indicative of processes associated to confined areas vs passages strongly 113 influenced by a connection to the surface, such as bat-related biocorrosion and condensation-114 corrosion. Here, the in-detail investigation of cave morphologies and stratigraphy, U/Th dating and 115 stable isotope analyses of speleothems and cosmogenic burial dating of sediments, support a novel 116 interpretation of the main processes leading to speleogenesis, occurring in a dynamic environmental 117 context of changing climate and landscape.

We take the Toirano karst system as an example of an enigmatic case study to suggest a guideline in the investigation of cave evolution, based on a correct interpretation of underground morphologies, sustained by geochemical analyses, anchored in time by dating and coherently integrated with surface events. Our results allow reconstructing the evolution phases of the cave system during the Quaternary, witnessing profound changes in the surrounding landscape.

123

124 **2.** Study area

The Toirano karst system develops along the lower slopes of Mt. Carmo di Loano (1389 m asl), half
a kilometre north of the small village of the same name (Savona Province, Liguria Region, northwestern Italy) (Fig. 1).



Fig. 1. Location of the study area and the Toirano Caves in Liguria, NW Italy. Refer to Fig. 2 forthe geological setting.

The caves develop in the slopes on the hydrographic left of the Varatella torrent, at the outlet of its gorges, upstream of the coastal plain; the shoreline is located only 4.5 km downstream from the caves. This area belongs to the Briançonnais domain of the Ligurian Alps, being part of a complex dome structure dipping here 20-30° toward the NE (Boni et al., 1971; Cavallo, 2001; Fig. 2). The *San Pietro dei Monti* Formation (Fm.) (Middle Triassic) constitutes the main local unit. Although mainly composed by dolostone, it presents a more calcareous lower formation (*Costa Losera Fm.*),
in which most caves are carved. Toward the south, the carbonate rocks are interrupted by a NE-SW
normal fault with a vertical offset of at least 200 m, that places the Middle Triassic dolostones in
contact with the quartzite of the *Ponte di Nava* Fm. (Lower Triassic in age) (Fig. 2) (Menardi
Noguera, 1984; Cavallo, 2001).

143



144

Fig. 2. Simplified geological map and profiles of the studied area (after Boni et al., 1971; Menardi
Noguera, 1984). Note the marine Pliocene deposits to the south.

148 It is along this major tectonic contact that the thermal spring of Toirano is located, on the hydrographic right side of the Varatella torrent and at an altitude of 70 m asl (Fig. 3). This spring 149 has a rather high mean discharge of 100 $L \cdot s^{-1}$ and delivers waters of 22-23 °C, with a slightly basic 150 pH (7.2-7.4) and moderate mineralisation (ca. 600 µS/cm at 20 °C, hardness of 23 °F); it consists in 151 a bicarbonate-calcium type water with low concentration in sulphates (25-37 mg L^{-1} SO₄²⁻) 152 153 (Calandri, 2001). These hydrogeochemical characteristics are stable year-round and even after 154 important rain and flood events, which would exclude significant mixing with shallow meteoric water and surface runoff from the Varatella torrent. The isotopic signature of the thermal spring 155 $(\delta^{18}O = -6.9 \% \text{ vs.} -5.8 \% \text{ at the coast})$, points toward a mean altitude of its catchment at around 156 400 m a.s.l, corresponding to a surface of at least 4 km² along the slopes of Mt. Carmo (Cavallo, 157 158 1990).

159



Fig. 3. View downstream on Toirano village and on the Varatella torrent from the entrance of
Colombo Cave. The Mediterranean shoreline is located 4.5 km southward, behind the hills (Photo
J.-Y. Bigot).

164

The Varatella torrent generated fluvial terraces that can be traced up to an altitude of ca. 100 m asl (Fanucci et al., 1987). In the neighbouring Ria of Albenga (5 km south of the study area, Fig. 1) there are remnants of two levels of Lower Pliocene shorelines located at 280-310 and 380-420 m

168 asl, showing a Plio-Quaternary uplift of the mountain front of at least 350-400 m (Marini, 2004). 169 Offshore, these Pliocene marine deposits, several hundreds of metres thick, are burying the deeply-170 incised Messinian canyon of the Centa River (Clauzon et al., 1996; Soulet et al., 2016). In the 171 Varatella valley itself. Pliocene remnants are very scarce, limited to a conglomerate outcrop in a 172 small plateau (45 m asl) at the outlet of the highway tunnel (Boni et al., 1971, Fig. 2). Its visible 173 part displays an inclined layer of cemented angular limestone blocks originating from the local hill, 174 resting on a sand bed. This conglomerate corresponds to inclined foreset beds of the Pliocene 175 Gilbert-type delta filling the Messinian canyon of the Varatella river. This canyon can be traced 176 offshore of Borghetto San Spirito, where it flowed together with the Centa Messinian canyon 177 originating from the larger valley of Albenga (Soulet et al., 2016). Apart from these conglomerates, 178 there is no indication of the inland extension of the Messinian Varatella canyon, which might have 179 been uplifted and probably eroded. Currently, in Toirano, the Varatella torrent flows on the 180 quartzite bedrock (Fig. 2).

181 Climate in Toirano is mild Mediterranean and maritime, warm and temperate, with an average 182 annual temperature of 14.3 °C (mean minimum of 6.6 °C in January, mean maximum of 22.6 °C in 183 July); annual rainfall is 830 mm with no pronounced wet season, while June and August are 184 essentially dry.

The Toirano karst system is composed of Ulivo Cave (*Grotta dell'Ulivo*, 337 m asl, 27 m long),
Colombo Cave (*Grotta di Colombo*, 247 m asl, 310 m long), Upper Santa Lucia Cave (*Grotta di Santa Lucia Superiore* or Sanctuary Cave, 215 m asl, 378 m long), Lower Santa Lucia Cave (*Grotta di Santa Lucia Inferiore*, 201 m asl, 778 m long) and the Bàsura Cave (*Grotta della Bàsura*, 186 m asl, 890 m long) (Chiesa, 2007; Gruppo Speleologico Cycnus and Delegazione Speleologica Ligure,
2001) (Fig. 4). A XV-XVI century church occupies the entrance hall of Upper Santa Lucia Cave;
the cave walls are decorated by pilgrims signatures since this time.



Fig. 4. Location of Toirano caves. The thermal spring is located nearby Certosa (see Fig. 3).

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Bàsura Cave owes its celebrity because of the presence of ancient human footprints, first believe to be of Neanderthal, but later shown to be of early Homo Sapiens groups (Citton et al., 2017); it was opened to the public in 1953, and in 1967 a 110-m-long artificial tunnel connected Bàsura with Lower Santa Lucia Cave (Gruppo Speleologico Cycnus and Delegazione Speleologica Ligure, 2001). The tunnel has allowed discovering some new natural cave passages that would otherwise have remained unknown, since they do not have natural access. The construction works have 202 emptied the lake that was present in the *Antro di Cibele* in the lowest part of the known Bàsura 203 passages. The drying out of this lake has generated an important exchange of atmospheric masses 204 between different cave branches, starting the circulation of large quantities of air in the cave 205 environment, a process that was previously lacking.

206 Sarigu (2001) and Calandri (2001) have described the caves of the area from a geological, structural 207 and geomorphological point of view, and gave the first detailed speleogenetic hypothesis. The caves 208 are often characterised by long passages with very low inclination, carving inclined strata. These 209 close-to-horizontal passages have probably developed along the former water table position. The 210 direction of the cave passages is greatly controlled by the main fracture sets in the region with 211 typical NE-SW directions (60% of all fractures), which are associated to the important uplift phases 212 of Pliocene age, and minor components in the N-S (15%) and W-E directions (25%) (Sarigu, 2001). 213 Most authors attribute cave formation to the Pliocene, related to the intense uplift of the region and 214 the opening of the ENE-WSW fractures (Sarigu, 2001), although some authors even mention a start 215 of cave-forming processes during the Lower Miocene (Fanucci, 1985).

216

3. Methods

We visited Toirano several times between 2015 and 2019 to carry out geomorphological observations and sampling in Bàsura, Lower and Upper Santa Lucia and Colombo caves. Sampling locations are reported in Fig. 5, whilst Figs. 6-9 report the most significant cave morphologies. Sediments and morphological features were considered within their spatial and stratigraphic relations, in order to attribute a relative chronology. Following our conservational purposes (Columbu et al., 2020), almost all samples were taken from fragments found broken on the ground, result of the constructional works outlined above.

Several mineral deposits showing peculiar characteristics at naked eye (i.e. colour, fabric, texture, morphology and stratigraphic location, see Tab. 1 for these observations and sampling location) were sampled in Colombo (n = 7), Lower Santa Lucia Cave (n = 10) and Bàsura (n = 5), and analysed with classical techniques X-Ray Diffractometry (XRD) and Scanning electron microprobe
(SEM) analyses at Genova University (Italy) and at CINaM (CNRS - Aix-Marseille University,
France. Full details on mineralogical analytical methods can be found in Audra et al. (2019). These
analyses aim to better understand the processes driving the deposition of such a variety of
secondary chemical deposits.

233 A sample of quartz- and feldspar-containing sands have been collected for Al-Be cosmogenic burial 234 dating at the ASTER AMS National Facility (CEREGE-CNRS, Aix Marseille University, France). 235 This is a well-established dating technique in karst-related studies, and full analytical details can be 236 found in Bella et al. (2019). The sampling site is located 50 m from the entrance of Colombo Cave, 237 shielded by a vertical rock thickness of at least 100 m, therefore no post-production was taken into 238 account in the burial age calculations. Indeed, in deeply incised mountain torrents like the study 239 area, production rates are not that influenced by the sourcing altitude because of the screening 240 effect. We assume that the samples were exposed at the surface over long times accumulating 241 nuclide concentrations, which started decreasing by radioactive decay once the sediments were buried in the caves. We used spallation production rates of 4.02 at/g/a for ¹⁰Be (Borchers et al., 242 243 2016), which are assumed to be constant over time and scaled for latitude and elevation (Stone, 2000). Muon contributions were scaled following Braucher et al. (2011). The ²⁶Al/¹⁰Be production 244 245 ratio induced by the standardisation used at ASTER (SM-Al-11/STD11) is 6.61 ± 0.50 . Only one 246 age was produced by this method.

Fragments of speleothems have been dated by the U-series method at the High-Precision Mass Spectrometry and Environmental Change Laboratory (HISPEC) of the National Taiwan University following established protocols (for detailed methods see Shen et al., 2012 and Columbu et al., 2019). A total of 13 ages were produced, targeting different speleothems such as: i) flowstones; ii) stalagmites; and iii) subacqueous mammillary and pool calcite, equally distributed in the four explored caves (see Tab. 2 for sampling sites and typology of dated speleothems). U-Th ages are here applied to estimate the minimal age of the caves, as well as give a broad temporal indication for different statuses of the underground conduits (i.e. vadose vs. subaqueous speleothems), as in Gázquez et al. (2018). Raw age calculations were executed by using half-lives, given in Cheng et al. (2013) and then corrected by assuming an initial 230 Th/ 232 Th atomic ratio of 4.4 ± 2.2×10⁻⁶. Ages are provided, throughout the text, by the ka notation (ka = thousand years before present).

A double-polished thin section has been prepared to study a calcite raft from Bàsura Cave (TO19 from Cibele room) for fluid inclusion petrography following the methods described in Krüger et al. (2011). The arrangement and characteristics of fluid inclusions are here taken as indication of the temperature of parent water depositing the raft.

Finally, stable isotopes of oxygen and carbon ($\delta^{18}O$ and $\delta^{13}C$ standardised to Vienna Pee Dee 262 263 Belemnite, VPDB) in calcite were measured at the University of Cambridge (UK) and Almeria 264 (Spain) with a precision better than 0.1‰ (for details see Gázquez et al., 2018). Sampling was carried out in Bàsura (n = 6) and Colombo (n = 1) caves, with the aim of targeting those 265 speleothems that could have potentially recorded signals of past hydrothermal activity. Indeed, $\delta^{18}O$ 266 267 has been used here to estimate the water temperature during calcite precipitation. This is because the ¹⁸O/¹⁶O fractionation factor between the mineral and the solution ($\alpha_{calcite-water}$) is sensitive to 268 temperature (Tremaine et al., 2011). This relationship is given by the expression (eq. 1): 269

$$1000 \ln \alpha_{calcite-water} = 16.1 (10^3 T^{-1}) - 24.6$$

271 where T is temperature (Kelvin degrees) and $\alpha_{\text{calcite-water}}$ is (eq. 2):

270

$$\alpha_{calcite-water} = \frac{\delta^{18}O_{calcite} + 1000}{\delta^{18}O_{water} + 1000}$$

273

In short, the $\delta^{18}O_{calcite}$ depends on the water temperature and $\delta^{18}O_{water}$ at the time of mineral precipitation. For calculations of palaeo-water temperatures in the Toirano caves we used: 1) the range of $\delta^{18}O_{calcite}$ obtained from the Toirano samples and 2) a $\delta^{18}O_{water}$ of -5.8‰ (V-SMOW), in line with the modern local mean values of $\delta^{18}O_{water}$ in rainfall (Cavallo, 1990); however, because the $\delta^{18}O_{water}$ of palaeo-water is unknown and may have changed with time as a result of varying climate, we used a range of ±0.5‰ for calculations.



Fig. 5. Simplified plan view of Colombo Cave (A), Upper Santa Lucia Cave (B), Lower Santa
Lucia Cave (C) and Bàsura Cave, reporting sampling (Survey courtesy of Gruppo Speleologico
Cycnus and Delegazione Speleologica Ligure, 2001). Blue circles correspond to calcite samples
collected for stable isotopes. Other samples are represented by red stars.

- 285
- **4. Results**
- 287
- 288 4.1. Cave morphology and deposits

The caves and their deposits will be described starting from the highest (Colombo Cave) to the lowest (Bàsura Cave). Simplified plan views and locations of the samples are reported in Fig. 3. The small Ulivo Cave, located almost 100 m above Colombo has not been investigated. However, its large portal opening to a short 27 m-long passage is here considered as the highest cave level of the system.

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295 4.1.1. Colombo Cave

296 Colombo Cave opens at 247 m asl. The wide entrance passage was used during prehistoric times, 297 and a 4.5 m-deep archaeological excavation pit is present 10 m from the entrance (Fig. 6B). 25 m 298 from the entrance, the passage opens in a large room of 10 m wide. In the bend of the passage, some 299 smaller ascending galleries open to the east. The room then turns into a more-narrow passage 300 towards the NE, where the cave continues for over 250 m in well decorated and faintly active (wet) 301 passages. The passage ends on a sediment plug, thus the morphology of the conduit and the type of 302 flow at the origin of the initial passage is not visible. This part was discovered after opening a 303 flowstone plug that only left a centimetre-space for air circulation. Nowadays a gate closes this 304 branch for conservation purposes.

305 The walls of the entrance passage and the main room have an overall smooth and wavy appearance. 306 The roofs are sculpted by cupolas and ascending channels, some are highlighted by the presence of 307 orange-coloured sediments (Fig. 6C). The main room is dominated by a large rock pillar standing at 308 its centre, being larger at its top and narrowing toward the floor (Fig. 6F). Along the archaeological 309 dig, the stratigraphy shows angular elements (cryoclastic material that has almost not been moved 310 from where it was formed). U/Th and ESR dating at 76-70 ka assign the lower part of the 311 excavation to Marine Isotope Stage (MIS) 5 (Pirouelle, 2006). Patches of coarse alluvial sediments 312 can be seen stuck on the limestone walls (Fig. 6A). Their rounded pebbles, made of both local 313 dolostone and allogenic material (quartzite, green schist), are up to 5 cm in diameter, and they are 314 cemented in a reddish matrix containing mica and quartz. Their source can be traced upstream in 315 the Varatella valley, where quartzite, polygenic conglomerates, and various metamorphic rocks 316 crop out (Boni et al., 1971) (Fig. 2). Similar alluvial deposits, but smaller size, are present in the 317 small ascending passage. In the inner portion of the cave, there are pockets of sands of similar 318 composition (Fig. 6C, H; TO6). The decrease of grainsize toward the cave interior testifies that 319 water, which deposited this material, came from the entrance. This material has been used for Al-Be 320 burial dating (Tab. 3). Remnants of old corroded flowstones can be seen here and there along the walls and have been sampled for U/Th dating (Tab. 2 and Fig. 6). On the contrary, shallow pools 321 322 with active speleothems are located behind the gate, where a rather important air circulation is 323 present. The floor of the central room is covered by dark bat guano deposits, most of which seems 324 to be rather old (Fig. 6F). Yellowish crusts (samples C1, C3, TO9a; Fig. 6G) and flowery 325 overgrowths have shown the presence of typical sulphate and phosphate minerals of guano decay, 326 including gypsum, ardealite, and newberyite, whereas leucophosphite was detected in samples 327 TO9a and TO9b (Audra et al., 2019). In the ascending passage, a brown crust (TO11) covering the 328 carbonate wall is composed of apatite (Tab. 1).





331 Fig. 6. Morphologies and deposits in Colombo Cave (Photos by Jean-Yves Bigot): A. Cemented 332 pebble deposit in a reddish loamy matrix, found outside at the entrance of Colombo Cave; B. The 333 archaeological excavation pit a few metres from the entrance; C. Rising cupolas filled with a calcite 334 coating (TO5) and a sandy deposit (TO6); D. Old corroded flowstone (TO7) at the entrance of the 335 large room; E. Old flowstone (TO8) sampled on the western wall of the room; F. Overview of the 336 central large room with the pillar, cupola on the ceiling, and abundant guano deposits; G. Yellowish 337 secondary minerals on guano (ardealite and brushite); H. Gravels sampled for cosmogenic burial 338 dating.

340 **4.1.2.** Upper Santa Lucia Cave

The first 50 m of the large entrance are occupied by the still active church. Visits were initially 341 342 possible using candles, then carbide lamps, the reason why the floor and walls have become 343 blackened by soot (Fig. 7C-D). The cave continues behind the altar. The passage ends in an old 344 flowstone, which has been damaged by explosives, probably in the hope of finding a continuation 345 of the cave. These "exploration" attempts however failed. Consequently, the characteristics of the original passage feeding the cave cannot be investigated. Most of the inner part of the cave shows 346 347 strong effects of condensation-corrosion as evidenced by smoothed walls and visible deep-inner 348 rings of flowstones (Fig. 7C). The roof is characterised by a never-ending network of 349 interpenetrating cupolas (Fig. 7D). In places, at the vertical of ceiling pendants where condensation 350 water concentrated, large dripping pots are developed (Fig. 7E). The floor is covered with patches 351 of old guano (Fig. 7D), and it is clear that large bat colonies inhabited the cave in the past. We 352 sampled an old corroded flowstone (TO3, 407.6 ± 22 ka) and a slightly younger rimstone (TO4, 353 343.0 ±10.4 ka; Fig. 7F, Tab. 2).



356 Fig. 7. Morphologies in Upper Santa Lucia Cave (Photos by Jean-Yves Bigot): A. The XV century 357 church in the wide entrance part of the cave; left to the altar, a door closes the inner part; B. Graffiti 358 on the walls in the inner cave (note writings of year 1687 to the left); C. Strongly corroded 359 stalagmite (1.5 m tall) with growth rings highlighted by soot veneer. Lateral calcite shelves, similar 360 to TO4, recording an ancient pool level, are visible on the walls; D. The final part of the cave with 361 corroded speleothems, coalescing cupolas, remnants of black soot on the walls, and a floor covered 362 with old bat guano; E. Biocorrosion cupolas (derived from bat and guano) and dripping-pots, which 363 are developing at the vertical of ceiling pendants that concentrate condensation runoff; F. The 364 sampled old flowstone (TO3) and the younger rimstone deposits (TO4).

366 4.1.3. Lower Santa Lucia Cave

Lower Santa Lucia Cave is located at 201 m asl, 14 m below and slightly south of the Upper Santa Lucia Cave. It splits into five distinct parts (Fig. 5C): the 200 m-long entrance gallery (*Tanone*), entering into the massif following a NE orientation; the *Capitelli* (the "Capitals") of the same direction; the Pantheon, a large descending circular chamber; the gallery of Pozzo dell'Ade, turning back SW toward the valley and from which depart two smaller side passages (Crystals Gallery II and III) and the artificial tunnel connecting with Bàsura Cave; and the Crystals Gallery I of the same SW direction.

374 The entrance gallery (*Tanone*), is a perfectly horizontal over 5 m wide and 10 m high passage, with 375 smooth corroded walls displaying a powdery dry aspect, and with almost no speleothems, except 376 for a few old corroded and massive flowstones. It looks more like a mining tunnel than a natural 377 cave (Fig. 8A). The Capitelli is isolated behind a passage opened through a calcite plug, now 378 equipped with a door that maintains the confinement of the inner part from the external air. Behind 379 this confining door, the cave appears as a completely different environment with respect to the outer 380 part, showing smaller dimensions and abundant flowstones. The Capitelli displays mushroom-like 381 speleothems, with a series of shelfstone levels growing at different heights above the cave floor, 382 culminating in a more extensively developed shelfstone level at 1.7 m height, forming the hats of 383 the mushrooms (Fig. 8C). The horizontal Capitelli passage then opens into Pantheon, a large 384 descending circular room, which is covered with calcite crystals (Fig. 8G). The room is decorated 385 with large stalagmites and stalactites, all showing a white and powdery corroded surface towards 386 the interior of the cave and deposition of reddish fines (toward the entrance) on the other side. The 387 warm and wet air flowing from inside the cave toward the entrance causes this corrosion. This 388 airflow is forced to pass a narrower passage, and this compression causes condensation on the 389 speleothem sides facing toward the Pantheon below. The reddish powdery coating on the other side 390 was probably produced during the excavation works. At the foot of Pantheon, the roof presents 391 multiple interpenetrating rising cupolas forming a giant rising channel morphology, indicating flow 392 rising from to NE, toward Pantheon that acted as a phreatic lift (Fig. 8H). The gallery of Pozzo 393 dell'Ade develops along a fracture parallel to the one that guided the first 200 m of the cave. Pozzo 394 dell'Ade is a large shaft, which bottom is not visible anymore, partly filled with tunnel construction 395 debris. On the current bottom of Pozzo dell'Ade, a narrow fracture-guided passage continues to the 396 E (Crystals Gallery III). This area is entirely covered with recent calcite and aragonite bushes and 397 crystals; it has not been investigated to avoid the damage to the delicate speleothems. Observations 398 of morphology and the original flow direction suggest Pozzo dell'Ade being the main source of 399 upwelling of deep water and this shaft can thus be considered as a major feeder of the original cave 400 system (Fig. 5C). Another fracture-controlled shaft is present 30 m further to the SW (Crystals 401 Gallery II), also not investigated for conservation purpose. This might be another feeder. Except 402 some small active epigene drippings, no other flow source has been detected.

The Crystals Gallery I develops after the artificial tunnel connecting to Bàsura Cave. Here, floor, walls, and roof are almost entirely covered with delicate bushes and needle crystals (Fig. 8I). Channelized flows of warm and moist air that condenses and partially corrodes the rock have carved condensation channels along the roof (Fig. 8I). When not covered with crystals coating, the host rock displays a deep weathered layer of soft red-brown material. Similar weathering material is also visible in places in the Gallery of Pozzo dell'Ade.

409 Fluvial deposits are visible only in a few places. In the entrance Tanone Gallery, a pebble deposit 410 has been found below one of the old flowstones (TO22, Fig. 8B). Some quartzite gravels clearly 411 show an external origin from fluvial material. In the excavated tunnel below Pantheon, a sand layer 412 (TO16b), also containing quartizte gravels, shows a progradant structure toward Pantheon, which 413 testifies to the ancient flow direction toward the NE (Fig. 8F). Finally, only fine clay sediments are 414 present in the Crystals Gallery (T10, T11), mainly composed of detrital material (quartz, feldspar, 415 muscovite/illite), and corresponding to the finer distal part of the coarse fluvial material identified 416 before.

Several calcite deposits have been sampled here for U/Th dating (Tab. 2). The *Capitelli* testifies to the presence in the past of large pools where outgassing caused the slow deposition of mammillary calcite and shelfstones (Bontognali et al., 2016; De Waele et al., 2018). The stipe of the "mushrooms", because of their typical steep conical shape, is probably formed by up to 2 m-high raft cones, although none is broken, so they might also be common stalagmites.

The crystals covering Crystals Gallery and the weathered material of the inner confined area have been sampled for mineralogical analyses (Tab. 1). In addition to calcite bushes and aragonite needles (Fig. 8I), the white soft porous deposits are made of hydromagnesite, dolomite, and magnesite (T5, T6), and the pasty moonmilk (T9) of calcite. The weathered rock materials (T7, T8, TO12) show the presence of hematite, goethite, muscovite/illite, and quartz, together with a large amount of calcite and dolomite host rock particles (Tab. 1).

Finally, large bat colonies were present in the past in entrance gallery (Tanone), as indicated by discrete remnants of phosphate crusts in cupolas. The guano deposit probably disappeared because of mining of local inhabitants and from the considerable reworking of the floor for the tourist trails. However, due to the presence of a thick calcite plug between *Tanone* and *Capitelli*, bats were not able to access the inner part of the cave that remained strictly confined.



434

435 Fig. 8. Morphologies and deposits in Lower Santa Lucia Cave (Photos by Jean-Yves Bigot): A. The 436 large Tanone gallery following the entrance displays walls with weathered rocky surfaces and very sparse remnants of corroded flowstones.; B. The fluvial pebble deposits (TO22) in Tanone gallery, 437 438 not far from the entrance; C. Capitelli, with the raft cones in the foreground, and the different levels 439 of shelfstones forming the mushroom-like speleothems; D. The end of the artificial tunnel shows 440 dark dolomite with white veins (left), where white mammillary (subaqueous) calcite (TO13) is 441 covered with a younger brownish calcite (TO14) representing a flowstone or shelfstone (subaerial); E. The top shelfstone of the mushroom-like speleothems (TO15), representing the youngest 442 443 generation of TO14; F. Gravel deposit (TO16b) just below the Pantheon, underlying a dated 444 flowstone level (TO16a); interpretation of progradation structure shows a palaeo-flow toward the NE; G. The nice Pantheon room, flow welled up from the hole below the person; H. The chain of 445

rising cupola between Pozzo dell'Ade and Pantheon also showing flow toward NE; I. The narrower passages in Crystals Gallery are entirely covered with aragonite and other white minerals, cut by a clear condensation-corrosion channel on the roof, where rock is deeply weathered (Photo by Philippe Audra).

450

451 **4.1.4. Bàsura Cave**

452 Bàsura Cave opens at an altitude of 186 m asl, with two neighbouring entrances less than 10 m 453 apart (Fig. 5D). Shortly after the connection of both entrances, there is the passage opened in 1953. 454 The horizontal passage gradually increases in size, then a large flowstone ascends toward the 455 Footprints Corridor. Several narrow passages on the NE side give access to side branches 456 descending to the lower parts of the cave (Fascio, Small Lakes). Proceeding inward, the passage is occupied by a lake, formed by recent infiltrating water, the only sign of temporary water flow in the 457 458 cave. A large rimstone dam is broken and has blocked the transport of large cave bear bones. From 459 here on, the floor of the cave is effectively a riverbed, and the related fluvial sediments are mainly 460 composed of clay with numerous cave bear bones and skulls. Then, the cave becomes narrower and 461 starts descending toward Cibele (Fig. 9B). In the lower segments, white subaqueous well-developed 462 speleothems indicate that this section has been underwater for a rather long period of time (Fig. 463 9C). Before its recent draining, this part of the cave was still underwater. On the bottom of Cibele, 464 the downward continuing branch is filled by blocks. An artificial 110 m-long tunnel connects 465 Bàsura to Lower Santa Lucia Cave.

Regarding the type of flow at the origin of the cave, the narrow side branches (Fascio, Small Lakes) descending to lower sectors, show signs of rising flow. These lower passages are most probably ancient feeders of the original cave system (Fig. 5D). It is highly probable that the downward continuing branch at the base of Cibele was another feeder of the original system. The main passage shows rising features, cupolas, widened fractures, rock fins. All is compatible with very slow 471 flowing water, completely lacking marks of turbulent flow such as scallops or allogenic coarse472 sediments.

473 Many signs of intense corrosion are visible throughout the main passage affecting walls, such as 474 widened corroded fractures and condensation-corrosion pits. Speleothems also show very clear 475 signs of corrosion especially in the vicinity of the side branches (Fascio, Small Lakes). Finally, both 476 entrances have become perfectly circular as the result of condensation-corrosion (Fig. 9A).

Two types of sediments are present. Close to the entrances, the floor is covered with angular cryoclastic elements showing an infill from external slope material. These sediments disappear inward, leaving place only to fine sediments. Only one place shows fluvial sediments, at the start of the steep descent towards Cibele: a sandy-gravel quartzose deposit in a red-brown matrix has been sampled (TO17, Fig. 9D).

Speleothems cover extensive surfaces (Figs. 9B, 9D). In Cibele, the passage is entirely covered by subaqueous mammillary calcite, which was still actively depositing before the artificial draining in the 60s (Fig. 9C). Cibele also displays pool fingers (microbial filaments gradually thickened by subaqueous mammillary calcite coating), which are up to 5m-tall and 20 cm of diameter. Such dimensions are probably unique for Europe. In addition, calcite rafts, after sinking down, were coated by up to 1 cm-thick subaqueous calcite (Fig. 9E).

488 Many speleothems have been dated by U/Th in the past, to constrain the human frequentation, 489 which is attested from at least 150 ka (Arobba et al, 2008) indicating that the cave was already 490 connected with the surface at that time. Footprints were instead left by Homo Sapiens around 14 ka 491 (Citton et al., 2017), attesting that the cave was still accessible. Indeed, the entrance flowstone 492 that closed the cave after human incursion reported an age between 205 ± 24 ka and 12.34 ± 0.16 ka 493 (Molleson et al., 1972). A large flowstone nearby the Footprints Corridor is certainly older than 615 494 ka. Indeed, the flowstone appears to have grown from the MIS13 (over 500 ka) to the beginning of 495 MIS7 (around 240 ka) (Pozzi et al., 2019). In addition to these previous studies, we collected three 496 calcite samples for U/Th dating (Tab. 2 and Fig. 9).

Three samples of calcite rafts have also been collected in Bàsura Cave for stable isotope analysis (Tab. 4, Fig. 5C): an active raft deposit in the lower parts of Fascio Branch (T2), and two thick rafts in the Cibele area, one on in the higher areas before descending (T4) and one in the lowest part (T3).

Finally, even if bats entered the cave before its artificial enlarging, guano deposits are not abundant. They possibly could be either covered by calcite or the size of colonies was limited by the narrow entrance. In a small alcove in the Fascio Branch, a brown crust has been sampled (TO21), corresponding to a bat guano by-product (F- or OH-apatite, with detrital contamination of quartz and mica).

506



510 Fig. 9. Morphologies and deposits in Bàsura Cave (Photos by Jean-Yves Bigot (A-D-F) and 511 Philippe Audra (B-C-E)): A. The rounded entrance of Bàsura Cave and the inclined strata; B. The 512 steep descent towards Cibele, cut through the thick flowstone; C. The subaqueous mammillary 513 calcite deposits of Cibele; D. The brownish sandy-gravelly deposits (TO17) below white calcite 514 (TO17); E. The thick calcite rafts on shelves in the massive pool fingers covered with mammillary 515 calcite; F. Subaqueous rafts integrated in a calcite sequence, sampled at the base of the Cibele room 516 (TO19).

518 **4.2. Mineralogy**

519

A wide array of minerals were identified by XRD and SEM analyses, and are reported in Tab. 1.
They belong to the classes of carbonates, sulphates, phosphates, oxi-hydroxides, and silicates.

522 Carbonates are represented by calcite [CaCO₃], aragonite [CaCO₃], dolomite [CaMg(CO₃)₂], 523 hydromagnesite $[Mg_5(CO_3)_4(OH)_2 \cdot 4 H_2O]$ and huntite $[Mg_3Ca(CO_3)_4]$. Pure calcite composes 524 rafts in Bàsura and Colombo caves (samples T3, T4 and C2), as well as the pasty material 525 (moonmilk) found in Lower Santa Lucia Cave (T9). Calcite and aragonite are the main components 526 of weathering material originating from the disaggregation of the walls, as expected in caves 527 developed in limestone and dolostone. It is often mixed with detrital material (T7, T8, T11, T12). In 528 Crystals Gallery, warm airflow causes the development of Mg-rich minerals growing on aragonite 529 frostwork, including huntite, and hydromagnesite, deriving from evaporation increasing the Mg/Ca 530 ratio of percolation and moisture at the contact of the walls (T5, T6, T1).

531 Oxides are represented by hematite $[Fe_2O_3]$ (TO9b, T8) and titanomagnetite $[Fe^2(Fe^{3^+}, Ti)_2O_4]$ (T7), 532 and hydroxides by goethite [FeO(OH)] (TO12). They may originate either from fluvial or detrital 533 material brought from the surface, or from weathering of detrital material through acidic bat guano, 534 or from red clay veins inside the rock.

Finally, silicates are represented by quartz, feldspar, and phyllosilicates (illite/muscovite, clinochlore). They are present in fluvial deposits (TO6, TO10, T11, TO16b, TO22, TO17), mixed as dust with other deposits such as guano (TO9a, TO9b) or phosphate deposits (TO11, TO21), or as constituent of weathered material associated with host rock particles (T8, TO12).

539

Table 1. Mineralogy of samples taken in the different caves (C = Colombo; LSL = Lower Santa
Lucia; B = Bàsura). Hm = Hydromagnesite; Hu = Huntite; Ar = Aragonite; Ca = Calcite; Do =
Dolomite; Gy = Gypsum; Br = Brushite; Ard = Ardealite; Nb = Newberyite; Le = Leucophosphite;

- Sp = Spheniscidite; Ap = Fluorapatite or Hydroxylapatite; Q = Quartz; He = Hematite; Go =
- *Goethite; Ma* = *Ti-magnetite; Il* = *Illite; Mu* = *Muscovite; Fs* = *Feldspar; Cl* = *Clinochlore*

ID	Cave	Sampling site	Observations	Minerals
C1	С	Main room	Hard yellow crystals on guano	Gy, Nb
C2	С	New branch after gate	Recent calcite rafts	Ca
C3	С	Main room	Yellow soft material on guano	Ard, Br
TO6	С	Ceiling pocket at entrance of chamber	Cemented sand, younger than TO5	Detrital (Q, Mu)
TO9a	С	Main Chamber, inner wall	Yellow gypsum flower	Gy, Le + detrital (Q, Mu/II)
TO9b	С	Main Chamber, inner wall	Beige phosphate deposit, drier than where gypsum is found	Gy, Le, He + detrital (Q, Mu/Il, Fs)
TO11	С	Side passage before chamber	Dark phosphate crust	Ap, Ca + detrital (Q, Mu/Il, Fs)
Т5	LSL	Crystals Gallery	White deposit on floor	Hm, Do
Т6	LSL	Crystals Gallery	White deposit on crystals on the wall	Hu, Hm, Do
Т7	LSL	Crystals Gallery	Weathered wall with boxwork	Ca, Ma
Т8	LSL	Crystals Gallery	Brick red weathering material	Ca + detrital (Q, Il, Cl), He
Т9	LSL	Crystals Gallery	Yellowish pasty material	Ca
T10	LSL	Crystals Gallery	Residual fluvial green-grey clay in fracture	Detrital (Q, Mu)
T11	LSL	Crystals Gallery	Fluvial sediment	Do + detrital (Q, Mu, Cl)
TO12	LSL	Above Pozzo del Ade	Weathered wall	Ca (75%) + detrital (Mu/Il, Fs), Go
TO16b	LSL	Gallery below Pantheon	Progradant sandy deposit below calcite (TO16a)	Rounded detrital elements (Q, quartzite, He/Go, Fs)
TO22	LSL	Tanone	Several samples of pebbles below old stalagmite	Rounded detrital elements (Q, quartzite, He/Go, Fs) in Ca cement
T1	В	Fascio, lower parts	White dots on the wall	Hm, Hu, Ar
Т3	В	Base Cibele	Old thin stratified calcite rafts	Ca
T4	В	Top of Cibele, first room	Thick calcite rafts	Ca
TO17	В	Slope down to Cibele	Sand below white calcite (TO18)	Rounded detrital elements (Q, quartzite, He/Go, Fs)
TO21	В	Fascio, small inlet in entrance series	Brown phosphate crust	Ap + detrital (Q, Mu/Il)

4.3. Geochronology

548	A summary of the obtained U-Th ages is reported in Tab. 2, which comprises the sampling
549	locations and field observations. The full U-Th dataset is instead provided in Supplementary Tab. 1.
550	²³⁸ U content of the dated samples spans between 1719.3 and 81.2 ppb (average: 400.7 ppb). With
551	the exception of TO5 sample, detrital ²³² Th contamination is low. The latter is expressed by the
552	^{230/232} Th activity ratio (Sup. Tab. 1), with higher ratios indicating low contamination and <i>vice versa</i> .
553	This guarantees that the resulting $\pm 2\sigma$ uncertainty is relatively low. The U-Th radiochronology

554 allows to attain ages back to 550-600 ka (Hellstrom, 2003); ages around this limit can report 555 relatively high uncertainties, because of the inaccuracies in measuring the very low content of 556 residual uranium. Ages beyond this limit cannot be constrained, and are reported as >600 ka. In 557 Toirano karst system, the dated samples span between 35.1 ± 0.3 ka obtained from mammillary 558 calcite in Bàsura Cave (sample TO20) to >600 ka for several samples (TO5, TO10, TO13, and 559 TO18) from Colombo, Upper Santa Lucia and Bàsura Caves (Tab. 2 and Sup. Tab. 1). Several speleothems resulted older than 500 ka, in Lower Santa Lucia (TO14, TO15 and TO16) as well as 560 561 in Bàsura (TO19). The remaining samples are comprised between 179.7 ± 4.1 (TO8, Colombo 562 Cave) and 407.6 \pm 22 ka (TO3, Upper Santa Lucia Cave), with TO4 and TO7 reporting intermediate 563 ages respectively at 343.0 ± 10.4 and 375.5 ± 14.8 ka.

Cosmogenic dating reported an age of 1.798 Ma (Tab. 3), with ¹⁰Be concentration at the upper limit. The latter impeded a reliable calculation of the relative uncertainty. Despite this limitation, and the non-replicated data, we believe this age is reliable enough considering the well-established applied methodology as well at the stratigraphic agreement with the ages obtained by U-Th dating.

568

569 Table 2. U-Th ages and relative 2σ uncertainties. Ages older than the limit of the U-Th method are

- 570 reported as >600 ka. Caves: C = Colombo; USL = Upper Santa Lucia; LSL = Lower Santa Lucia;
- 571 $B = B\dot{a}sura$. See Suppl. Tab. 1 for the complete U-Th dataset.

ID	Cave	Age (ka) $\pm 2\sigma$	Sampling site	Observations
TO5	С	>600	Entrance Central Room	Calcite layer older than TO6
TO7	С	375.5 ±14.8	Entrance Central Room	Corroded flowstone
TO8	С	179.7 ±4.1	Central Room	Old corroded calcite in pocket
TO10	С	>600	Lateral branch of Central Room	Old white calcite floor
ТОЗ	USL	407.6 ±22	After station 10	Old stalagmite
TO4	USL	343.0 ±10.4	After station 10	Border of less old rimstone dam
TO13	LSL	>600	Entrance Capitelli	Subaqueous calcite older than TO14
TO14	LSL	577.2 ±60.6	Entrance <i>Capitelli</i>	Pool calcite, younger than TO13

то15	LSL	541.4 ±105.5	Entrance <i>Capitelli</i>	Upper part of <i>Capitello</i>
TO16	LSL	581.3 ±143.3	Passage below Pantheon	Calcite layer on sands
TO18	В	>600	Down to Cibele	White calcite covering sands of TO17
то19	В	562.3 ± 77.1	Bottom Cibele before tunnel	Old subaqueous calcite in Cibele
TO20	В	35.1 ± 0.3	Small Lakes	Mammillary calcite

573 Table 3. Cosmogenic burial age of quartz gravels in Colombo Cave (C). (*) = due to ^{10}Be 574 concentration at the upper limit, uncertainty could not be calculated, ASTER, 5MV AMS facility.

ID	Cave	Sampling site	¹⁰ Be (at/g)	²⁶ Al (at/g)	Burial age (Ma)
ТО	С	Inner wall of central room	8 453*	$24\ 621\pm 15\ 053$	1.798

575

576 4.4. Stable isotopes and temperature estimates

577 Stable isotopes of the selected samples range between -4.4% to -5.9% VPDB and -8.24% and -10.02‰ VPDB in $\delta^{18}O_{calcite}$ and $\delta^{13}C_{calcite}$, respectively (Tab. 4). Regarding $\delta^{18}O$ -derived 578 temperature, estimates are represented in Tab. 4 using the range of obtained $\delta^{18}O_{calcite}$ and the mean 579 value (-5.2% VPDB), in relation to the modern $\delta^{18}O_{water}$ (-5.8 ± 0.5 % V-SMOW). Uncertainties in 580 the latter limit the calculation of precise paleo-temperatures, so the results are here presented as a 581 broad estimate by using the symbol "~". The estimated uncertainties for the palaeo-temperatures is 582 around ± 3 °C. Our calculations suggest that water temperature has never exceeded ~23 °C (when 583 using values of -5.3‰ and -4.4‰ for $\delta^{18}O_{water}$ and $\delta^{18}O_{calcite}$, respectively) and was not lower than 584 ~10 °C (when using values of -6.3‰ and -5.9‰ for $\delta^{18}O_{water}$ and $\delta^{18}O_{calcite}$, respectively), during the 585 precipitation of calcite speleothems in the Toirano caves. 586

Table 4. Speleothem calcite stable isotopes ($\delta^{18}O_c$ and $\delta^{13}C_c$) and estimated palaeo-temperatures (local $\delta^{18}O_w = -5.8$ %, from Cavallo, 1990). C = Colombo; B = Bàsura.

ID	Cave	Location	$\delta^{18}O_c$	δ ¹³ C _c	Modern δ ¹⁸ O _w	T (°C) estimate	T uncertainty estimate (°C)
C2	С	Old calcite raft	-5.90	-8.24	-5.8	~20	$\sim \pm 3$
T2	В	Active calcite raft	-5.37	-10.02	-5.8	~17	$\sim \pm 3$
Т3	В	Calcite raft, lower part of Cibele	-4.98	-9.66	-5.8	~15	$\sim \pm 3$

T4	В	Calcite raft, upper part of Cibele	-5.70	-10.65	-5.8	~19	~±3
TO18	В	Old flowstone (>600 ka), Upper Cibele	-5.12	-8.17	-5.8	~16	~±3
TO19	В	Old flowstone (562 ka), Lower Cibele	-5.24	-9.32	-5.8	~17	~±3
TO20	В	Recent mammalies (35 ka), Lakes	-4.40	-9.09	-5.8	~12	$\sim \pm 3$

Transmitted-light microscopy has revealed the presence of primary monophase fluid inclusions in sample TO19 (Fig. 10). The inclusions show characteristic inverted edges, indicating their primary origin. Primary monophase fluid inclusions either appear isolated (Fig. 10A) or are clustered in fluid inclusion assemblages (Fig. 10B). No primary two-phase fluid inclusions were observed in this sample. The occurrence of only monophase liquid inclusions imply that mineral crystallisation occurred in a low-temperature (ambient-like) thermal environment, certainly less than ~50 °C.

597



598

Fig. 10. Examples of primary all-liquid fluid inclusions in TO19 calcite (a, b). Fluid inclusions
show characteristic inverted growth steps (b). Photomicrographs are the courtesy of Yves Krüger.

601

602 **5. Discussion: speleogenesis of Toirano karst system**

603 **5.1 Morphological indicators of speleogenesis**

Although the original shape of the caves and their meso-morphologies have been greatly modified

by later processes, several morphological observations in the different caves have shown a series of

606 important speleogenetic indicators:

607 1. The different remnants of the cave system are developed along clearly distinguishable levels, at 608 altitudes of 340 (Ulivo), 250 (Colombo), 215 (Upper Santa Lucia), 210-205-200 (Lower Santa 609 Lucia), and 185-175-165 m asl (Bàsura), respectively (Fig. 11). These subhorizontal cave passages 610 are clearly recognisable in the four upper caves, and are less clear only in Bàsura Cave, albeit still 611 distinguishable and comparable with cave passages at similar altitudes in Lower Santa Lucia Cave 612 (Fig. 11). These cave levels do not appear to have been influenced by local structural features 613 (i.e.strata are tilted), and their very low inclination (close to horizontal) can best be explained by 614 their evolution close to the former water table. These cave levels testify to relative long-lasting 615 stable phases in which the local base level and caves were at the same altitude.

616 2. Morphologies suggesting fast and turbulent flow (scallops) have not been detected. Clastic 617 sediments range from gravel to clay. Apart from angular clasts located in entrance areas (especially 618 Bàsura), which have been brought in by gravity or by solifluxion, the largest elements (pebbles) are 619 located close to entrances with inward grain size decrease, clearly pointing toward intrusions of 620 allogenic fluvial material. This is also evidenced by their petrographic composition (quartzite, 621 schist), which agrees with the source areas located nearby the Toirano area (Fig. 2). Cave passages 622 have been entirely filled by these sediments, at least for the first 100-200 m from the entrances. In 623 the inner parts of the system, only smaller grain sizes are visible (gravels, sands), as long as they are 624 not concealed by later speleothem deposition. Samples TO16 and TO17 show a reworking of the 625 allogenic material by internal flow toward outlets that maintained their activity during the infilling 626 periods. Finally, fine sediments derive from a mixing of different sources, i.e. carbonates grains 627 from disaggregation of the host rock, clays and iron oxides from insoluble material and red clay 628 veins, and from allogenic fluvial sediments, as evidenced by typical minerals (quartz, mica, 629 feldspars) trapped in the weathered material along the walls.

630 3. The caves are characterised by morphologies suggesting slowly flowing waters, and it is clear
631 from observations in several cave areas that these fluids followed ascending paths. These
632 morphologies are rising channels, superposed cupolas and ceiling channels. Some ascending

633 conduits are almost certainly ancient feeders. Except from limited seepage spots, no trace of 634 significant epigene recharge, either active or inactive, such as vadose shafts and meanders, have 635 been detected. The hydrological circulation at the origin of the cave system is clearly hypogene 636 (*sensu* Klimchouk, 2007), implying upward recharge from a deep route, with surface water 637 minimally influencing flow discharge and the chemico-physical characteristics of the fluids. Several 638 morphologies detected in the Toirano karst system are similar to a recent case study where phases 639 of hypogenic speleogenesis have been well documented (Pérez-Mejías et al., 2019).

640 4. Condensation-corrosion, both by convection of external warm and wet air masses, and vapours 641 produced by bats and decay of guano deposits, have intensely modified walls and roof 642 morphologies in many portions of the caves, especially in the higher parts of the system that were 643 not confined (Colombo, Upper and Lower Santa Lucia caves). This has made it difficult to 644 recognise many of the typical morphologies of rising flow.

5. The active thermal and slightly sulphidic spring in the village of Toirano, less than 700 m south of the caves and ~100 m below the Bàsura Cave, indicates ongoing processes of deep fluid circulation today. Analogously, deep fluid circulation might have been active in the past; hypogene fluids circulating in the carbonate rocks would have caused the formation of the karst network.

649



Fig. 11. Schematic profile through Mt. Carmo showing the altitudinal distribution of the cave levels
in relationship to their hypogene origin, the uplifting and correlated Varatella valley deepening
(Surveys courtesy of Gruppo Speleologico Cycnus and Delegazione Speleologica Ligure, 2001).

654

655 **5.2. Hypogene origin of the system**

The mineralogical analyses did not evidence the typical weathering by-products of sulphuric acid speleogenesis such as alunite and jarosite (D'Angeli et al., 2018). In addition, there are no massive gypsum deposits, and the observed tiny gypsum minerals were always associated to guano deposits. Instead, carbonate minerals abound, including calcite, aragonite, huntite, and magnesite (minerals typically found in dolostone-hosted caves), whereas gypsum, ardealite, brushite, F- and OH-apatite, leucophosphite/spheniscidite, and newberyite have been found on the old guano deposits (Audra et al., 2019, Tab. 2).

663 The caves formed within the carbonate rock mass without a direct connection to the surface, and 664 before the Varatella torrent started carving its deep valley. Possibly thermal fluids rose along deep-665 rooted sub-vertical faults concentrating their corrosive action close to the water table, where the 666 dissolved CO₂ was able to escape into the above lying air-filled chambers. Most dissolution 667 occurred close to the water-air interface, and in the aerate part of the caves because of 668 condensation-corrosion. The action of minor amounts of H₂S-enriched fluids cannot be entirely excluded, based on the sulphide amount of the spring still active today (25.4-37.0 mg L⁻¹; Calandri, 669 670 2001), although clear evidences of sulphuric acid speleogenesis (SAS) have not been found. 671 However, the signs of sulphuric acid interaction with the host rock, both weathering products 672 (gypsum and other sulphates) and typical corrosion morphologies (e.g., replacement pockets), could 673 have been easily weathered by the intense and long-lasting condensation-corrosion processes, 674 and/or covered by the recent action of infiltration waters and speleothem deposition. It is more likely that the cave-forming fluids were rich in CO₂, and might have been slightly thermal, whereas 675 676 sulphate (and sulphuric acid) played only a minor role (if at all). Accordingly, we claim that the Toirano caves are of hypogene origin, with the earliest speleogenesis governed by the upwelling ofpossibly low thermal fluids rich in CO₂.

679 Stable isotope analyses, however, have pointed to palaeo-temperatures ranging from $\sim 12 \pm 3$ to ~ 20 680 \pm 3°C (Tab. 4). Considering uncertainties, temperature estimates never exceed ~23°C and were 681 never lower than ~10°C. Such values span between the current temperature found at the active 682 thermal spring of Toirano (22-23°C) and the present climate in the valley (Toirano city 14.3°C). 683 This variability could be related to the different climate periods during which calcite deposited. 684 Accordingly, recent (35 ka) mammillary calcite of "Small Lakes" (T20), deposited during the last 685 glaciation, reported the lowest estimate (12 ± 3 °C, Tab. 4). Active rafts reveal a temperature of 686 \sim 17°C, which is close to the current cave temperature and mean annual average, and lower than the 687 thermal spring temperature. Ancient flowstones (TO18-19) and rafts (T3-4) show a temperature 688 range between ~15 and ~19 °C (Tab. 4), likely driven by palaeoclimate changes as quoted above. 689 The presence of all-liquid primary fluid inclusions in one of the calcite rafts from the Cibele area 690 also suggests that the mineral depositing fluids were characterised by temperatures lower than 691 ~50°C (non-hydrothermal) (Fig. 10). We suggest that all cave calcite deposited from infiltrating waters, at times mixing with slightly thermal water. The calcite δ^{13} C values (between -8 and -11%), 692 693 Tab. 4) are consistent with a contribution from above lying soils rather than a pure hypogene flux (McDermott, 2004). This is confirmed also by the δ^{18} O values, which are typical of low temperature 694 695 calcites precipitating from mid-latitude rainfall waters (Columbu et al., 2018). The fact that the last 696 glacial T20 sample reported the lowest temperature supports that infiltrating water had a primary 697 role in speleothem precipitation.

Most of the calcite speleothems visually appearing as very old deposits reported ages beyond the U-Th method limit (ca. 600,000 years), even in the lower (and possibly youngest) caves (Tab. 2). The age of underground deposits can be used to constrain the minimal age of the cave (Columbu et al., 2015; 2017). Consequently, the entire karst system and even the lower cave levels are certainly older than 600 ka. Similar results were obtained by Bahain (1993), with the base of a flowstone in Bàsura Cave showing reverse magnetic polarity (thus certainly older than 780 ka); ESR dates of faunal remains in this basal sequence reported ages between 502 (\pm 47) and 748 ka (\pm 66), whilst several U/Th dates resulted older than 557 ka (Shen, 1985). This is also confirmed by recent studies in Bàsura Cave, where the bottom of a 2 m-thick flowstone resulted older than 615 ka (Pozzi et al., 2019).

708 The allogenic sands sampled in Colombo Cave have delivered a burial age of approximately 1.8 709 million years, which represents the minimum possible age of the voids filled by these sands. These 710 coarse-to-fine sands have been carried into the caves during the Lower Pleistocene high stands, by 711 rivers that aggraded their thalwegs because of the rising sea level. During the Gelasian (ca. 2.6-1.8 712 Ma) the sea level, which greatly controlled the base level for the studied caves, oscillated globally 713 between -100 and +10 m with respect to present sea level (Rohling et al., 2014). By considering the 714 \sim 1.8 Ma age in Colombo, and the elevation of the cave over the Varatella valley (\sim 180 m), the resulting incision rate can be estimated at 0.1 mm y^{-1} . The incision of the Varatella valley possibly 715 716 responded to the uplift of the area north of the main fault (on which the thermal spring is located). 717 This rate is slightly overestimated (Colombo Cave is older than 1.8 Ma, so the real incision rate is 718 lower), since the cave formed before the intrusion of the dated sands (possibly at the Upper 719 Pliocene/Lower Pleistocene). However, this value is in agreement with the long-term uplift rates estimated in a coastal area 20 km East of Toirano (e.g., 0.086-0.20 mm y⁻¹ in Carobene and 720 Cevasco, 2011; 0.08-0.16 mm y⁻¹ in Carobene and Firpo, 2002). Taking into account the estimation 721 of the incision rate of the Varatella valley (0.1 mm y^{-1}), we can tentatively estimate the age of all 722 723 cave levels: Ulivo Cave might have an age of ~2.7 Ma, Colombo Cave would have formed around 724 1.8 Ma (given the cosmogenic dating), Upper Santa Lucia Cave 1.5 Ma, Lower Santa Lucia 1.3 Ma, 725 and Bàsura Cave around 1.2 Ma (Tab. 5). According with our estimates, the speleogenesis of the 726 Toirano cave system occurred during the Gelasian and Lower Calabrian, and probably at the very 727 end of Pliocene for the highest Ulivo Cave. The presence of a Messinian canyon offshore, and 728 Pliocene Gilbert-delta deposits onshore in the vicinity of the current coastline, evidence that the 729 valley significantly entrenched during the Messinian Deep-sea-level, then was refilled during the 730 Pliocene by sediments sourced from the ongoing uplifted mountain where strong erosion occurred. 731 The discontinuous uplift of the study area mainly took place during the Upper Pliocene - Lower 732 Pleistocene, with marine Lower Pliocene sediments now located at altitudes of up to 400 m asl 733 (Carobene and Firpo, 2002; Ferraris et al., 2012). Then, following the Pleistocene uplift, a gradual 734 entrenchment of the Varatella gorge occurred, with the removal of most of the Pliocene marine 735 deposits and Pleistocene terraces. The old fluvial material, located above 100 m asl, has only been 736 preserved in Toirano caves as intrusion material. They are possibly related to 1) aggradation or 737 fluvial intrusion during Pleistocene, or 2) re-incision and injection in caves of the reworked 738 material. The cosmogenic burial age at about 1.8 Ma, if reliable, would point toward the second 739 option. Note that Colombo Cave predates this age, without indications on how much older this cave 740 could be with respect to the sediment intrusion. Regarding ages obtained from speleothem U/Th 741 dating, most are older than the method's limit (600 ka), making it difficult to ascribe an age to the 742 subaqueous deposits related to the initial phreatic stage. However, the partial draining of the main 743 pool stages (Capitelli in Lower Santa Lucia and Cibele in Bàsura, which are located at the same 744 elevation), probably still fed by minor hypogene recharge, is quite well bracketed around 581-541 745 ka. Considering the age errors, this would correspond to a period between ca. 720 and 440 ka (Tab. 746 2 and 5). The pool-stage record in the well-marked shelves of Upper Santa Lucia is more recent 747 $(343 \pm 10 \text{ ka})$, even if the cave is located slightly higher. This would indicate that portions of the 748 main cave levels (USL-LSL-B, see Tab. 2 for codes) were underwater for approximately 400,000 749 vears, comprised approximately between 720 and 330 ka. The age of dated stalagmites, which could 750 have developed during or after this active hypogene pool stage, confirms the partial or complete 751 draining as early as 400 ka. Flowstones older than 500 to 780 ka in Bàsura (Shen, 1985; Bahain 752 1993, Pozzi et al., 2019) suggest that some parts of the cave system were drained earlier.

Cave	Alt. (m)	Proposed age of phreatic hypogene speleogenesis (Ma)	Agepoolspeleothemsandflowstones (ka)	Age stalagmites (ka)
Ulivo	337	~2.7		
Colombo	247	~1.8	> 600	376, 180
Upper Santa Lucia	215	~1.5	343	408
Lower Santa Lucia	201	~1.3	581-541	
Bàsura	186	~1.2	562 - 35	
Thermal spring	70	Active		

756

757 **5.3 Overprinting of late stage condensation-corrosion**

758 5.3.1 Condensation-corrosion in the inner semi-confined parts of the cave system

759 Intense signs of condensation-corrosion are visible in the inner parts of the caves that were almost 760 entirely confined before the artificial opening of the tunnel and calcite plugs, such as in the inner 761 branches of Colombo Cave, in the (past) confined part of Lower Santa Lucia Cave, and especially 762 in the Crystals Galleries. Here, walls are covered by boxwork and deeply weathered soft material in 763 between, with red-brown or greenish coloured surfaces (Fig. 12A), whereas the dolomite host rock 764 was originally black (Fig. 8D). The weathered soft layer is several centimetres thick. It is mainly 765 composed of loose carbonate grains with a high porosity (>25-30%), with minor amounts of iron 766 oxyhydroxides (hematite, goethite, Ti-magnetite) at the origin of the typical colour, and detrital 767 minerals (quartz, mica, feldspars, illite). Carbonates are provided by the disaggregation of the host 768 rock, detrital minerals are remnants of old sediment filling of fluvial origin brought from external 769 sources, and iron oxyhydroxides originated either from host rock veins of red clay, or from the 770 weathering of the detrital minerals.





Fig. 12. Condensation-corrosion evidences: A. The black dolomite rock is deeply weathered by condensation-corrosion, making boxwork and soft residual material. Note the coating of evaporite minerals (calcite, aragonite, huntite, and hydromagnesite) (Photo by Jo De Waele); B. Air mass stratification in Crystals Gallery produces a sharp limit between areas of evaporation-precipitation downward and condensation-corrosion in the upper parts (Photo by Philippe Audra).

779 Many places in these confined parts are covered by a secondary carbonate coating, composed of 780 minerals that are typically found in caves hosted in dolostone (calcite, aragonite, huntite, and 781 hydromagnesite). This coating is present in the lower parts of the passages (lower walls and floor), 782 whereas the upper parts generally display boxwork and weathered layers (Fig. 12B). Both are 783 closely associated. In cave atmosphere close to moisture saturation, subtle air convections allow air 784 mass stratification and exchange; condensation of higher warm moisture occurs on the cooler 785 ceiling, whilst evaporation occurs in the lower parts of the passages in cooler and drier airflow. 786 Condensation produces corrosion on the ceiling and a weathered layer, whereas evaporation 787 produces crystallisation in the lower parts. The solutes produced by condensation-corrosion in the 788 higher part of the passages descend by gravity across the weathered layer on top toward areas of 789 evaporation at the bottom, where mineral precipitation can occur. The subtle airflow, currently 790 present in the Crystals Gallery, which is directed toward the external cliff, clearly shows a still

791 active process. Here a recent corrosion channel carves the white speleothem coating and the 792 bedrock along the roof of the passage (Fig. 8I). However, such slow process requires long time to 793 produce such deeply weathered layers. It possibly started after the early stages when hypogene 794 caves began draining, but when slightly thermal water was still present at depth, or at least when the 795 rock mass was still heated by the thermal fluids, producing rising warm and moist air flows. These 796 processes clearly postdate the initial phreatic hypogene stage, which would have washed away the 797 soft weathered material. Since many speleothems are older than 600 ka (Tab. 2) and some even older than 780 ka, one can expect that the condensation-corrosion process in confined cave areas 798 799 occurred from about at least 1 Ma. The successive openings to the surface of some entrance parts 800 drastically changed these semi-confined conditions, starting much more active condensation-801 corrosion processes boosted by active air circulation between the external atmosphere and the inner 802 cave portions.

803

804 5.3.2. Condensation-corrosion and biocorrosion in the large entrance parts

805 Condensation-corrosion is particularly evident in the large passages of Colombo, Upper and Lower 806 Santa Lucia, and in Bàsura caves. Importantly, the caves are located on a southwest facing cliff, 807 where warm and wet air masses from the sea frequently rise along the valley and cause the 808 formation of coastal fogs. During summers, the air masses coming from the sea have average 809 temperatures well above 20°C, able to produce condensation on the cave walls that are around 810 15°C, or even colder. Furthermore, efficient air circulation prevents the cave atmosphere to warm 811 up because of the release of condensation latent heat, keeping the cave walls colder than the 812 entering air, and thus sustaining a continuous production of condensation waters. In the lower parts 813 of the cave passages, dripping condensation waters, containing dissolved carbonates, fall to the 814 ground and evaporate, causing the deposition of new microcrystalline calcite that is mostly removed 815 by airflow. The highly undersaturated condensation waters have produced the weathering (partial 816 dissolution) of the rock walls causing their powdery appearance.

817 In Lower Santa Lucia, the entrance passage (Tanone) is intensely corroded by condensation, mainly 818 due to its large entrance allowing warm moist air circulation. Most of the flowstones have 819 disappeared, except in sheltered corners (Fig. 8B). Here, remnants of coarse pebbles cemented by 820 an old flowstone show that the passage has been entirely cleaned from its fluvial filling. It now 821 displays as a large rounded conduit, with smooth wavy walls and a light colour due to the thin dry 822 weathering layer (Fig. 8A). Compared to the passage size beyond the calcite plug isolating the 823 Capitelli from Tanone, it clearly appears that Tanone conduit significantly expanded by 824 condensation-corrosion, probably for several metres, cancelling most of its original features and 825 sediments.

826 In Bàsura Cave, condensation-corrosion morphologies are also clearly visible: i) at the entrances, 827 where the initially elliptical phreatic conduits have been subsequently rounded (Fig. 9A); ii) 828 immediately behind the small passage that was opened in 1953; iii) on walls and speleothems 829 intensely corroded by airflow. Here condensation is possibly related to the variations in pressure of 830 the airflow, when the passage was still closed, and airflow experienced important pressure 831 variations. This is confirmed by the fact that the signs of corrosion are most evident in the first ten 832 metres from the (originally) narrow passage. In the Footprints Corridor, several speleothems are 833 deeply corroded by airflows. Here, condensation is probably caused by the formation of a mixing 834 cloud (Badino, 2010), since air convection from lower branches (Fascio, Small Lakes) mixes with 835 air masses in this part of the cave. In addition, widened corroded fractures and condensation-836 corrosion pits, which are strongly developed, testify the intense activity of the process in this area.

The condensation-corrosion process is also boosted by bat colonies, which abundant presence in the past, considering the larger colonies and higher variety of species is testified by the large old guano and phosphate deposits. Phosphate forms crusts on carbonate walls and calcite speleothems mainly composed of F- and OH-apatite, whereas leucophosphite/spheniscidite form in presence of clastic material. More recent and still decaying guano is covered by sulphates and phosphates such as gypsum, ardealite, brushite, and newberyite (Tab. 1; Audra et al., 2019). Guano decay is an exothermic process releasing both water vapour and carbon dioxide, thus enhancing condensation above the guano heaps, and causing high CO₂ levels in the air. Other acids released by guano decay make the atmosphere particularly aggressive and corrosive. In addition, bat exhalations add other considerable amounts of heat, vapour, and carbon dioxide. All these aggressive solutions combine and are responsible of the biocorrosion of cave floor, walls, and ceiling, where cupolas are the most expressive features (Lundberg and McFarlane, 2009, 2012, 2015; Audra et al., 2016; Dandurand et al., 2019).

850 This powerful process can explain the exceptionally wide central room in Colombo Cave, where a 851 central biconcave rock pillar is the leftover of intense expansion of original passages by 852 condensation-corrosion (Fig. 6F). The same is testified by the presence of old corroded flowstones, 853 as well as typical morphologies such as cupolas and the wavy (mega-cusped) appearance of the 854 cave walls. Additionally, the pebbles that were introduced into the cave, and that probably entirely 855 filled it, have completely disappeared, leaving only some patches of planed conglomerates in 856 sheltered niches. Last but not least, the scarcity of graffiti (i.e. visitors' signatures) remnants shows 857 the ongoing activity of corrosion processes. Based on our observations, the wall retreat by 858 biocorrosion processes alone can here be estimated in at least 1 m on both sides of the passage, 859 probably double on the roof.

860 In Upper Santa Lucia Cave, masses of old guano are still visible. Biocorrosion features are intensely 861 developed. Interpenetrating cupolas are carving the chamber ceilings, cutting both rock and old 862 calcite speleothems (Fig. 7D). Dripping pots are developing on the vertical of ceiling pendants that 863 concentrate condensation runoff (Fig. 7E). However, on the contrary to Colombo Cave, actual 864 biocorrosion processes seem to be subdued, as testified by the considerable amount of well-865 preserved graffiti, even on top of cupolas that are the places of the most intense condensation. This could be explained by the continuous frequentation of the cave by pilgrims and by the gating of the 866 867 inner part (Fig. 7A) that prevented intrusion of bats for centuries, and thus preserved the historical 868 traces of frequentation.

870 **6.** Conclusions

871 On the basis of the geomorphological observations, supported by geochemical analyses and 872 radiometric dating, the origin of these complex caves cannot be attributed to a "classical" epigene 873 vadose and phreatic speleogenetic model only. The Bàsura-Santa Lucia-Colombo caves formed by 874 the action of rising hypogenic fluids that followed deep-rooted subvertical fractures. The rising 875 conduits (feeders) are still visible in the lower levels of the cave system (Bàsura and Lower Santa 876 Lucia caves), whereas they are obliterated in the higher and older levels by abundant authigenic and 877 residual sediments. In the lower passages, the traces of ascending fluids are still well visible in 878 many areas, with rising channels and superimposed cupolas.

879 Based on the observations made in the highest of the studied caves (Colombo) the following 880 speleogenetic scheme can be presented (Fig. 13): A) The cave started forming at the water-table 881 level fed by a deep-rooted fracture, with slightly thermal (possibly H₂S-rich) waters carving the 882 cave in both phreatic, but mainly aerate conditions; B) A marine transgression during the final 883 phases of the Pliocene and Early Pleistocene caused the river valleys to aggrade and enlarge; the 884 entrance of the cave was completely filled with gravels and sands (pockets on the roof of the cave 885 are still filled with remnants of these sediments, which burial age is around 1.8 Ma); C) successive 886 Pleistocene uplift phases of the mountains caused the Varatella torrent to entrench, partially 887 emptying the cave which, at least in the early stages, was probably still actively enlarging by rising 888 hypogene fluids. The continuous uplift caused the intersection of the water table with the feeding 889 fractures to shift laterally and to lower elevations, causing the formation of the lower levels of the 890 cave system; D) in the final stages the cave system was abandoned by flowing hypogenic waters, 891 and since then the large cave entrances are affected by air circulation, bat roosting and 892 frequentation. Condensation-corrosion processes started to remove most remnants of the older 893 sediments and speleothems (several of which are beyond the U/Th dating limit, i.e. > 600 ka).



Fig. 13. Evolution of a given level of Toirano caves (especially Colombo and Lower Santa Lucia). 895 896 A. Horizontal cave connected to base level develops with hypogene upflow and condensation-897 corrosion in the confined part. B. Fluvial aggradation (Early Pleistocene) rises the base level and 898 fills the entrance passages with coarse fluvial material. C. Subsequent base level drop following the 899 continuous uplift allows reopening of the cave with partial removal of the fluvial filling. D. Because 900 of slope retreat, condensation-corrosion occurs in the still confined portions of the cave through 901 geothermal effect, with more effective corrosion in the entrances accessible to moist external air 902 and bat colonies.

904 Only in more recent times, at least 150 ka (based on the oldest archaeological findings), but 905 probably much earlier, the entire cave system fully connected with the external atmosphere, 906 initiating the air circulation and local condensation-corrosion processes. All signs of vadose flow 907 visible today are to be connected to recent invasion or interception of small inflows or infiltrations 908 in the pre-existing hypogenic cave system.

The intense condensation-corrosion, still very active today, has erased many of the morphologies and deposits of the original hypogene speleogenetic phase. The presence of large bat colonies appears to have a strong influence on later vadose condensation-corrosion processes, playing an important role in shaping the voids they occupy. Wall retreat by sole condensation-corrosion can be estimated in over 1 metre in the highest caves (Colombo) due to the combined action of air circulation and bat colonies. Condensation-corrosion, however, is also active in more recently opened caves such as Bàsura, and warrants attention in the future for conservational issues.

We suggest taking this study as a guideline for a thorough investigation of cave evolution, based on
a correct interpretation of underground morphologies, sustained by geochemical analyses, anchored
in time by dating and coherently integrated with surface events.

919

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