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Paleokarst coastal caves at Torricelle Hills (Lessini Mountains, Venetian Prealps, Italy)

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Abstract: This paper describes a set of paleokarst caves at Torricelle Hills near Verona (Southern Alps, Italy.) At this locality, erosional surfaces and paleokarst cavities show that sedimentation of late Paleogene neritic limestones was interrupted by subaerial exposure. Karst features developed during a phase of marine regression that started after the early Oligocene and ended in the mid Miocene. These caves were originally completely filled by iron oxides- and hydrated oxides-rich paleosol sediments (ochre) that, for centuries, have been mined for pigments. Mining activity emptied the caves, leaving the voids and related shapes mostly intact; as a result, the original morphologies have been exhumed, making these caves a rare example of explorable paleokarst. These "ochre caves" were mapped in a series of surveys over a few years. The exploration of overall 4.5 km of accessible passages in four caves yielded a wealth of information on speleological features, stratigraphy, paleontology, and paleogeography, and here we exploit this information to infer the genesis of these unusual caves. Their evolution started in phreatic conditions, characterized by very slowly moving or still waters that led to the formation of solution facets. A vadose phase of development ensued, followed by infilling by reworked soil-derived sediment and associated paragenetic modifications. Sediment accumulation ended with the complete fossilization of the caves under epiphreatic conditions. Siliciclastic and carbonate sediments containing littoral fossils indicate that the caves developed in the vicinity of a coast, and that they were subject to marine ingression. Overall, these paleokarst coastal caves seem to be a fossilized example, well preserved and explorable, of the Carbonate Island Karst Model on larger islands. We interpret these caves as conduits that drained the freshwater lens in a spatially limited carbonate peninsula that existed in this part of the Lessini paleocoastline between the Oligocene and the Miocene.

Keywords: Cave sediments, ochre, paragenesis, coastal karst, Lessini Shelf

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INTRODUCTION

For several centuries, ochre-colored oxides and hydrated oxides of iron (earlier known as limonite, hereafter refer to as ochre) were quarried in the limestone hills around Verona, called Torricelle (Lessini Mountains, Southern Alps, Italy) and was employed as pigment for art and architecture (Scarzella & Natale, 1989). Miners excavated large seams of relatively soft ochre, scraping it away from the surrounding host rock that was left mostly intact. Excavation left a network of galleries that today extends for many kilometers and is still partly accessible.

At the end of the XIXth century, the karstic nature of the ochre seams was recognized; they were actually ochre-filled caves (Nicolis, 1898). Removing the ochre fills, miners exhumed a fossilized paleokarst network in what is now known as one of the most densely karstified areas in the Southern Alps. Estimates suggest that at least 20 km of galleries develop in the Torricelle Hills, in an area of less than 2 km^2 (Forlati, 1978). The discovery of terrigenous-calcarenitic layers containing foraminifera alternating with reworked paleosol fills provided evidence that karst development began in the late Eocene and ended in the early Miocene (Gonzato et al., 2014).

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These "ochre caves" have not been studied exhaustively. In fact, most previous research on the paleokarst network at Torricelle Hills focused on the age, origin, and geochemistry of the ochre fills (e.g., Zorzin & Latella, 2007; Gonzato et al., 2014; Cavallo et al., 2015). These studies did not discuss much of the morphology, speleogenesis, evolution, and fossilization processes of the caves. To address this lack of information, we started surveys at Torricelle Hills with the aim of identifying and surveying the caves that were still accessible, contribute with additional speleological, stratigraphic and paleontological data, and attempt a data-driven reconstruction of their evolution.

This paper focuses on the caves morphologies, sediment fills, and evolution of the four ochre caves we could explore. Overall, these caves exhibit an unusual set of features that, to the best of our knowledge, have not been reported in other Italian karst areas. We put forward the hypothesis that this paleokarst may represent a fossilized example of the conduit flow caves described by Larson & Mylroie (2018) for large carbonate islands.

The peculiar set of features of Torricelle caves makes them a very unusual, if not unique, type of paleokarst. Many studies on paleokarst concentrate on mineralization and bauxitic deposits associated to paleokarst (see for instance Boni & D'Argenio, 1989; Bosák et al., 1989). Others describe relict surface and subsurface forms (James & Choquette, 1988). In general, it is common for paleokarst caves to be either destroyed by denudation or to be filled with sediments and/or minerals.

In contrast, the Torricelle paleokarst network is explorable, at least in part, because the lateritic colluvial fills have been mined, allowing exploration and study that would have been impossible in other paleokarsts. As a result, we were able to examine the cave patterns, morphologies, several types of fills and sediments, as if these were ordinary caves. Fossiliferous and siliciclastic fills, in particular, have been used to provide chronologic and paleogeographic information.

GEOLOGICAL SETTINGS

Torricelle Hills are the southern edge of Lessini Mountains, a carbonate plateau that lies at the SW of the Venetian Prealps, bordering the Po Plain north of Verona (Southern Alps, Italy; Fig. 1). The plateau is one of the major Italian karst areas, comprising over 750 mapped caves and, at higher altitudes, well developed karst landforms (Pasa, 1954; Sauro, 1973; Mietto & Sauro, 2000).

The sequence of sedimentary rocks is more than 1500 m thick and includes carbonate formations ranging from the late Triassic to the middle Miocene. The area belongs to a major Jurassic structural element of the Southern Alps, the Trento Platform (Winterer & Bosellini, 1981), surrounded by the Lombardy Basin to the West and the Belluno Trough to the East (Fig. 1A). The Trento Platform deepened and drowned in the middle Jurassic; shallow water conditions were restored in the early Eocene. The resurrected carbonate platform is known as the Lessini Shelf (Bosellini, 1989).

Carbonate formations are crossed by volcanic pipes, dykes and sills of Paleocene-Oligocene basalts and pyroclastic rocks (Piccoli, 1966; Antonelli et al., 1990; De Vecchi & Sedea, 1995). Thick deposits of lateritic paleosols, the result of subaerial exposure of volcanic products, are common in the Eastern Lessini and in Val d'Alpone (Piccoli, 1966).

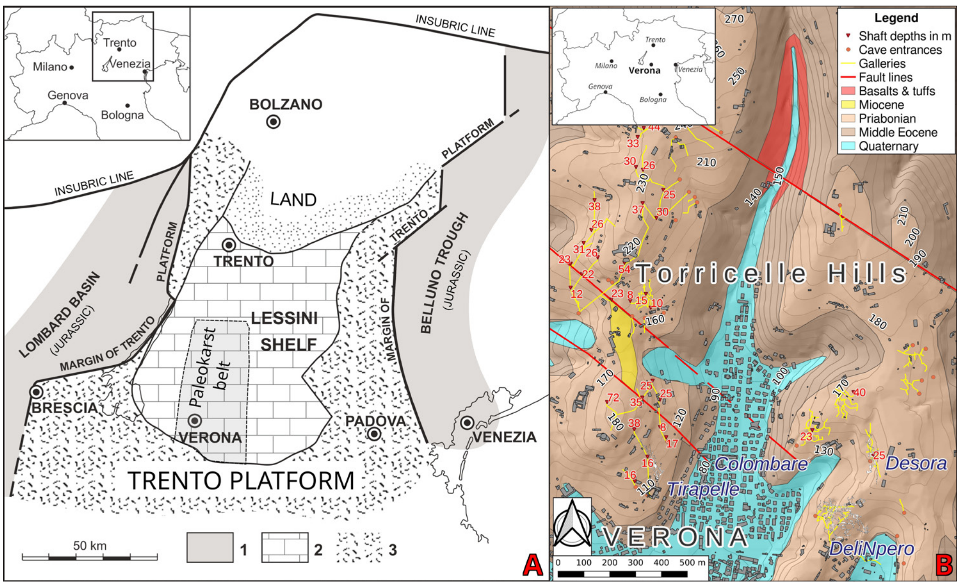

Fig. 1. Study area. **A:** Verona and its location at the southern edge of the "paleokarst belt" in the Lessini Mountains. 1: Lombard Basin and Belluno Trough (Jurassic); 2: Lessini Shelf (Eocene); 3: Trento Platform (Jurassic). **B:** Geological map of the Torricelle area (modified after De Zanche et al., 1977) and cave locations (modified after Forlati, 1978).

The plateau is basically unfolded, but is affected by NNE-SSW tectonic lineages to the west (Giudicarie compressional fault system, Serravallian-Tortonian) and by NW-SE transfer faults to the east (Schio-Vicenza system, Messinian-Pliocene; Castellarin & Cantelli, 2000). Rock beds dip slightly southwards; Mesozoic formations crop out in northern and central areas, while Cenozoic formations occur mainly at the southern edge.

The Eocene succession at Torricelle Hills and nearby areas consists of neritic Lutetian-Bartonian bioclastic limestones ("*Calcari Nummulitici*") and Priabonian marly limestones (Priabona Formation). There are also minor patches of middle Miocene (Serravallian-Langhian) epineritic/littoral biocalcarenites, along with outcrops of middle Eocene basalts and tuffs (De Zanche et al., 1977). Late Eocene and Miocene sediments show indistinct bedding; occasionally, differential weathering reveals the presence of beds that dip slightly (~5°) towards S-SSE. All currently known paleokarst caves at Torricelle develop between the upper *Calcari Nummulitici* and the lower Priabona Formation.

A stratigraphic gap extends between the late Eocene and the middle Miocene. Erosional surfaces, products of subaerial weathering of rocks, and paleokarst, enable attribution of the gap to a phase of marine regression (Fabiani, 1915, 1919; Conato & Martinis, 1955; De Zanche et al., 1977). Oligocene sediments are also missing in the central Lessini Mountains, although they may have been removed by erosion. Only a tiny outcrop of early Oligocene sediments has been reported at Cavalo, about 17 km to the NW of Torricelle (Castellarin & Farabegoli, 1974). At Torricelle, clasts of early Oligocene limestone have been found in the conglomerate at the base of the Miocene calcarenites (Fabiani, 1915). The phase of marine regression therefore began at some point after the early Oligocene and ended in the middle Miocene.

The presence of residual sediments and paleokarst suggests that marine regression also affected an area of the central Lessini Mountains, approximately 30-km wide and N-S oriented, which we define as "paleokarst belt" (Fig. 1A). As in the Torricelle Hills, but much less developed, paleokarst fissures and minor cavities are filled with limonitic residual sediments (Ponte di Veja, Rocca di Rivoli, Val Sorda, S. Giorgio di Valpolicella; Gonzato et al., 2014). Cave passages filled by basalts have also been reported in the central Lessini Mountains (Rossi & Zorzin, 1986; Gonzato et al., 2017). Basalts have been dated to the late Eocene-early Oligocene (Piccoli, 1966), and provide additional evidence that karst was already active in this period.

METHODS

We first tried to identify the caves of Forlati (1978), who mapped 64 entrances on Torricelle Hills. Regrettably, most cave entrances are now buried and/or filled with rubble. Furthermore, many cave entrances have been lost and forgotten. As a result, only four caves have been found and explored: Grotta DeliNpero, Grotta Via Tirapelle, Grotta Desora, and Grotta Colombare (Fig. 1B). The total length of the explored passages is 4.5 km.

All caves have been surveyed and thoroughly photographed, taking note of all relevant geological features. Surveys were finalized using Open Source spreadsheet LibreOffice Calc and GNUPlot scripts. Three-dimensional maps have been obtained with Mathematica (v. 13.0, Wolfram Research Inc.). A few samples have been collected to provide paleontological data; in particular, we employed the screenwashing technique (Cifelli et al., 1996) to extract minute fossils (mesh size 1 mm) from weakly cemented fills.

Cave plans and geological features have been compared to those of non-paleokarst caves in the Lessini Mountains, highlighting the unique features of the Torricelle paleokarst. Statistical analysis of survey data was used for further characterization. Statistical methods and results have been described in the accompanying Supplemental Information document.

PREVIOUS RESEARCH

The ochre caves at Torricelle were commonly referred to as "mines", given the great importance of local ochre exploitation through the centuries. This denomination misled many cavers, who were not interested in exploring supposedly artificial cavities. As a result, only a few studies have been performed, mainly on the ochre fills, and very few cave surveys are available (Zorzin & Latella, 2007).

The karstic origin of the ochre outcrops in the Torricelle Hills was first recognized by Nicolis (1898), who noticed that the large ochre "lodes" in Eocene limestones were actually fossilized karst cavities with rounded morphologies; outcropping vertical crevices filled with ochre lead miners to the main passages. Nicolis (1898) also reported the first chemical analysis on a single ochre sample, highlighting high contents of Fe, Si, Al, and Mg oxides. Works by Federici (1948) and Cavallo & Zorzin (2008) and Cavallo et al. (2015) highlighted a variable composition of these ochres, generally characterized by high contents of goethite and hematite and, in some specimens, large amounts of quartz. The composition of these materials is consistent with a provenance from lateritic soils, suggesting that they originated in a hot and humid tropical climate (Tardy, 1997).

Very few studies have dealt with the dating of the paleokarst phenomena; this has been a difficult task, because of the lack of index fossils in the ochre fills. However, bioclastic layers have occasionally been found sandwiched between the ochre fills. The first of such layers was found at Grotta Via Sbusa by Corrà (1977), who reported a generic Miocene age; his dating was based on unspecified nannoplankton. Corrà (1977) also described epikarst features, such as solution pipes, at the erosional discontinuity between the upper Priabona Formation (late Eocene) and the Miocene calcarenites.

Zorzin et al. (1992) based their dating on palynological analysis and ochre samples from Grotta Tirapelle yielding tropical plant pollen (*Magnoliaceae*, *Palmae*, *Pinaceae*) of generic late Neogene age. Finally, Gonzato et al. (2014) found layers of fossiliferous calcarenites embedded in ochre at Grotta Desora and Grotta Tirapelle. Foraminifera assemblages yielded, respectively, a late Eocene (*Discocyclina*, *Nummulites*) and a generic late Oligocene-early Miocene (*Lepidocyclina*, *Miogypsina*) age.

While no previous works focused specifically on karst morphologies and speleogenesis, a few observations are available. Vadose morphologies were recognized by Forlati (1978) and Zorzin & Latella (2007), who also described ceiling channels at Grotta Tirapelle.

Corrà (1977) mentioned several ochre caves on the western Torricelle Hills; their number and locations are currently unknown. He pointed out that ochre fills in these caves were always topped by calcarenite layers of presumed Miocene age. In his interpretation, cave fill and fossilization were caused by marine inflow that eventually drowned the caves during an early Miocene transgression.

CAVE DESCRIPTIONS

In all explored caves in the Torricelle Hills, most of ochre excavation took place by digging away the relatively soft ochre until the harder host rock of the cave walls was reached. This method preserved and exhumed the original shape of the cavities, highlighting the original morphologies. In very few cases, passages were enlarged using explosives; materials were piled up at the sides, masking the morphologies for short sections.

The bottom part of many passages is often masked by sediment; therefore, we might have failed to observe structures developing at the floor level. Moreover, the weak mechanical properties of the Priabona Formation marlstones caused some passages to collapse. Nevertheless, cave morphologies are generally visible, although scratched by tool marks. Remarkably, all morphologies are beveled and rounded, indicating corrosion.

Grotta DeliNpero

Cave location: Verona, Via Castello S. Felice, third hairpin turn, WGS84 coordinates N 45.451685, E 11.004874, altitude of entrance 117 m (Fig. 2A); lithology: transitional boundary between upper Calcari Nummulitici (Bartonian) and lower Priabona Formation (Priabonian). The cave is registered in the Italian National Cave inventory as 8675-V-VR.

This cave is very well preserved; only the lower sections of a few passages were enlarged by miners, and in general the original morphology is intact. Some ochre deposits are still in place.

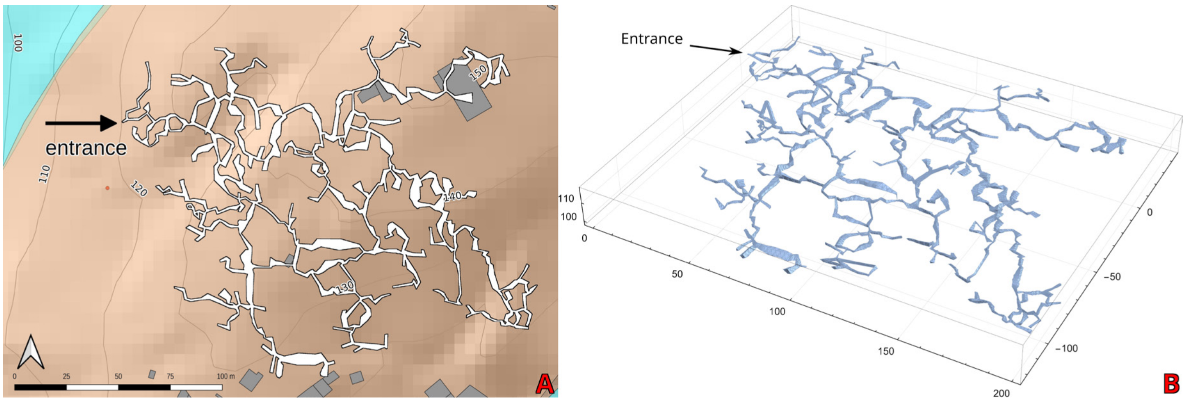

Fig. 2. Grotta DeliNpero. **A:** Cave plan and location; **B:** Three-dimensional map of Grotta DeliNpero, highlighting the limited vertical development of the cave. X and Y axes show distances in m from the entrance; Z axis shows the elevation in meters above sea level.

Morphology

The cave plan can be described as a bidimensional anastomotic maze (Fig. 2B); this pattern has never been observed in other Lessinian caves, nearly all of which are simple vadose shafts, single passage, or rudimentary branch caves in the classification proposed by Palmer (1991). The surveyed cave length exceeds 2400 m, but the actual cave extension is unknown; a few passages, in fact, were not excavated and are still filled. Passage density, calculated by polygon density, is a remarkable 92.5 km/km^2; this feature is unique to this cave.

As passages develop approximately on a single plane that is slightly tilted towards the SSE, in conformity with the local stratigraphy, we assume that the cave was tectonically tilted. The cave is horizontally extensive but is vertically restricted to a few metres. More precisely, the plane is interrupted by a normal fault that lowers the NE part of the cave by approximately 2 m. Passage directions are apparently random (see Supplementary Fig. S1, Supplementary Fig. S2, and Supplementary Table S1).

The majority of passages exhibit the same morphology. A flattish and low crawlway constitutes the passage vault; flat or convex facets are incised at the bottom, and a narrow meander develops downwards (Fig. 3A, B). This T-shaped morphology makes passages hardly distinguishable from each other. Width is reduced to less than 1 m and height is 1.5 m on average, and loops are frequent.

A minority of cave passages connecting the T-shaped meanders are vertical slots that feed the fills to the horizontal main passage (Fig. 3C); occasional lamination is present and is always vertical. We suppose that these slots correspond to the crevices described by Nicolis (1898). The presence of vertical lamination was also observed in the other surveyed caves and suggests that the caves were filled under vadose conditions.

The cave vault is nearly always erosional. In some cases, it is flat, but more often it is slightly dome-shaped, and in a few cases, it is incised by large and very shallow coalescent cupolas (Fig. 3D); a few examples of corroded pendants and a set of ceiling half tubes have also been observed (Fig. 3E).

Isolated hemispherical cupolas up to 1 m in diameter can occasionally be observed. Some of these features are only half excavated, showing ochre lamination that apparently fills them from the bottom upwards (Fig. 3F). Upwards convex lamination was systematically found in all explored caves. Along with convolute lamination that is occasionally very well developed, this feature seems to suggest that in some cases the fills were pushed in (sediment weight or seismicity), rather than simply washed into the caves. The fill emplacement mechanisms, however, remain unknown.

Ochre fills have sometimes caused paragenetic modifications of the original cave morphology. The shape of the majority of passages shows that they developed as low vadose canyons; at a later stage, alluviation of ochre sediments originated vadose and paragenetic wall notches, which are always visible at passage sides (Fig. 3B). Distinguishing between the two is not always easy; paragenetic notches can be easily identified in inclined passage areas, since they have the same gradient as the passage (Farrant, 2004; Farrant & Smart, 2011). It should be stressed that notches are not associated to bedding planes, which cannot be seen in the host rock.

Fig. 3. Common features at Grotta DeliNpero. **A:** Passage morphology: flat roof, lateral inclined facets, and shallow vadose entrenching; **B:** Vadose entrenching showing paragenetic notches; **C:** Vertical fissure, possibly conveying ochre from the paleosurface; **D:** Flat dome-shaped cupolas; **E:** Remnants of ceiling channels on eroded roof; **F:** Section of cupola showing convex ochre lamination.

Sediments and fills

The main feature of this cave is the ubiquitous ochre fill that is still visible in nearly all passages. A thin coating of yellow-brown ochre clings over nearly all cave features. Although excavation removed the fills quite thoroughly, miners did not clear the cave walls of the last few millimeters. As a result, the host rock is rarely visible and is always “dirty”. Only a few passages are perfectly clean of ochre coating and lack tool marks; we suppose that these passages may have never been filled entirely.

Ochre fills occur as thinly laminated clay and silt (Fig. 4A); color is mainly yellow-brown, but pale grey and shades of red and purple are not uncommon. Ochre laminations are still observed at the crawlway sides, which were uncomfortable to reach and in consequence were left intact by miners. In most cases, laminae are parallel to the underlying morphology of the cave walls.

Large boulders are sometimes found in the ochraceous matrix. Frequent breccia layers, convolute lamination, and microfaults displacing the cave walls and the fills by a few centimeters, perhaps indicate tectonic activity and/or passage collapse (Fig. 4B, C). At least to some extent, breakdown occurred during passage formation and was followed by ochre sedimentation. Some breccia layers contain angular fragments of the Eocene limestone from cave walls and of a dark grey sandstone that comes from a layer outcropping 20 m above the cave (Fig. 4B). Breccia layers and some examples of convolute laminations may be the result of seismic activity; high-angle faults, displacing passage morphologies, can be attributed to passage settlement and partial collapse.

Microfaults and fissures in the host rock are very common and are always filled with ochre; as a result, water circulation is almost completely absent. The cave is therefore still fossilized and very little dripwater was observed even during very wet events that flooded the other caves in the area.

Non-ochre fills are quite rare in this cave. We observed only two outcrops of siliciclastic fills: gray, fine-grained arenites and greenish glauconitic arenites (Fig. 4D, E).

Fine-grained arenites onlap on a passage wall and show parallel and cross lamination. The material contains grains of glauconite, biotite, muscovite, and bioclasts, including a benthic foraminifera (*Nummulites*?).

Glauconitic arenites have very limited horizontal extension and a thickness up to 2 cm. In this material, screenwashing yielded a fossil assemblage that includes fish teeth, reworked benthic (*Amphistegina* sp.) and well preserved (*Dentalina* sp.) foraminifera, brachiopods, echinoid plates and spines (diadematids), crinoid ossicles, and bryozoans (Fig. 4F). The assemblage can be attributed to a littoral or neritic environment.

Fig. 4. Fills at Grotta DeliNpero. **A:** Parallel ochre laminations; this is the most common fill in the surveyed caves; **B:** Breakdown of cave walls material in ochraceous matrix; **C:** Convoluted lamination in ochre fill; **D:** Fossiliferous siliciclastic fill; **E:** Thin layer of fossiliferous glauconitic arenite; **F:** Fossil assemblage in the glauconitic arenite. From the top, clockwise: fish teeth; echinoid plate and spines; reworked nummulitids; brachiopod shells; bryozoans; well preserved foraminifera (*Dentalina* sp.).

Grotta Tirapelle

Cave location: Verona, Via Tirapelle 6, WGS84 coordinates N 45.453069, E 10.997197, altitude of entrance 112 m (Fig. 5A); lithology: topmost beds of Calcari Nummulitici (late Bartonian); inventory number 5661-V-VR. The surveyed cave length is nearly 950 m; a blocked passage in the northern branch probably leads to unexplored galleries. This is the best preserved of all explored caves; nearly all passages are virtually intact. However, several branches and the lower part of nearly all passages were not excavated; therefore, morphologies are only partially visible.

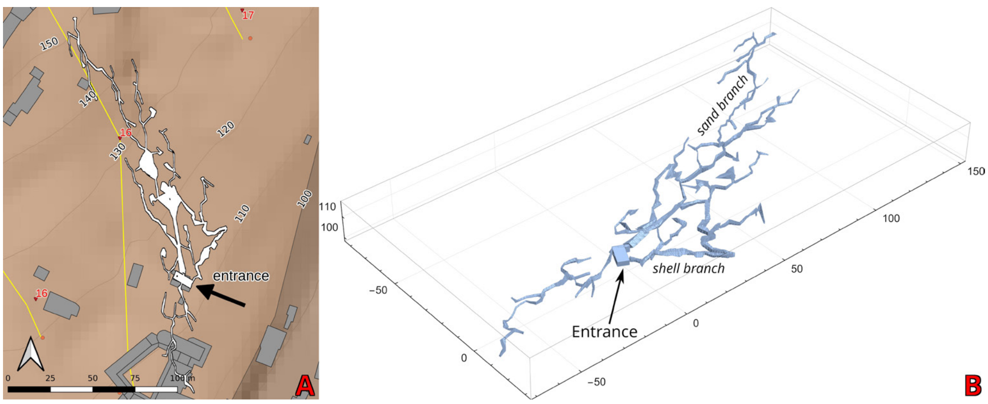

Fig. 5. Grotta Tirapelle. **A:** Cave plan and location; **B:** Three-dimensional map of Grotta Tirapelle, highlighting the limited vertical development of the cave. X and Y axes show distances in m from the entrance; Z axis show the elevation in m above sea level.

Morphology

This is a branchwork cave showing a well-defined NNW-SSE orientation (Fig. 5B; see also Supplementary Fig. S3). The cave age was established by means of foraminifera assemblages to be late Oligocene-early Miocene (Gonzato et al., 2014).

The main gallery was excavated in the top 2 m and artificially enlarged, as it was used as bomb shelter during World War II; some passages are connected to the main passage floor, revealing its real height. All passages develop in a single plane (Supplementary Fig. S4 and Table S2); the vertical extension of the cave is no more than 6 m.

The morphology of the galleries is quite different from that of Grotta DeliNpero, where nearly all passages are low, T-shaped, meandering vadose canyons. At Grotta Tirapelle, many passages are linear and taller (up to 6 m), have parallel sides incised by wall notches, and exhibit flat ceiling incised by channels (Fig. 6A, B). Overall, some of these passages resemble paragenetic canyons. Other passages are reminiscent of the T-shaped morphology of Grotta DeliNpero, exhibiting facets in the upper part of the passage and relatively shallow, non-meandering vadose incisions (Fig. 6C). Paragenetic wall notches are ubiquitous; anastomotic and linear ceiling channels are also quite common.

Remarkably, part of Shell Branch was not artificially excavated, and a vadose phase of development removed the fills almost completely and smoothed the passage sides, including layers of carbonate fills. Ceiling channels and wall notches are especially developed in this branch (Fig. 6D).

Finally, a few passages (Sand Branch) are vertical slots from which ochre, red and green arenites were washed into the cave; sediment lamination is nearly vertical in the slot (Fig. 6E) and turns horizontal at the passage sides.

Fig. 6. Common features at Grotta Tirapelle. **A:** Tall meander with flat ceiling and paragenetic notches at the sides; **B:** Paragenetic notches and ceiling channel; **C:** Triangle-shaped passage with lateral facets, wall notches, and very short vadose entrenching; **D:** Passage showing lateral facets, vadose entrenching, wall notches, and ample ceiling channel; **E:** Sand Branch: vertical laminations of red and green fossiliferous arenites.

Sediments and fills

Three main types of fill have been found. The most common fill consists of calcareous-marly fossiliferous layers, a few centimeters to some decimeters thick, occasionally with grains of quartz, biotite, and muscovite. This fill, which is often sandwiched between ochre layers, is commonly found in the upper part of ceiling channels (Fig. 7A).

In thin section, the most common fossils are fragments of bivalves, benthic foraminifera that can be attributed to the Oligocene-Miocene (*Amphistegina* sp., *Operculina* sp., *Lepidocyclina* sp., *Miogypsina* sp.), and worn Eocene foraminifera (*Nummulites* ex gr. *fabiani*, *N.* ex gr. *incrassatus*, *Discocyclina* sp.; Gonzato et al., 2014).

At Shell Branch, a marly fill containing abundant pectinids of several species (*Pecten* sp., *Aequipecten* sp., and others unidentified) and other bivalves extends for a few meters (Fig. 7B, C). Abundance of pectinids makes this sediment very similar to local Miocene deposits ("*Calcareniti a pettinidi*"; De Zanche et al., 1977).

At Sand Branch, fills consist of red and green glauconitic sandstones (Fig. 8A) containing thick cidaroid spines (*Prionocidaris* sp.; Fig. 8B) and bivalves. Screenwashing yielded a rich fossiliferous assemblage that includes complete tiny echinoids, both regular and irregular (*Echinocyamus pseudopusillus*, *Genocidaris* cf. *catenata*), loose plates and spines of echinoids (cidaroids, diatematids), benthic foraminifera (*Bolivina* sp., *Dentalina* sp.), brachiopods (*Aphelesia* sp., *Argyrotheca* spp., *Terebratulina retusa*), bryozoans, and fish teeth (Fig. 8C).

To the best of our knowledge, fossils of this assemblage, which can be attributed to a littoral or neritic environment, have never been previously reported in the Torricelle area.

Fig. 7. Common features at Grotta Tirapelle. **A:** Cross section of a ceiling half-tube; the fill consists of alternate layers of fossiliferous sandstone and brown ochre; **B:** Marly fill with pectinids; **C:** Detail of the pectinid fill.

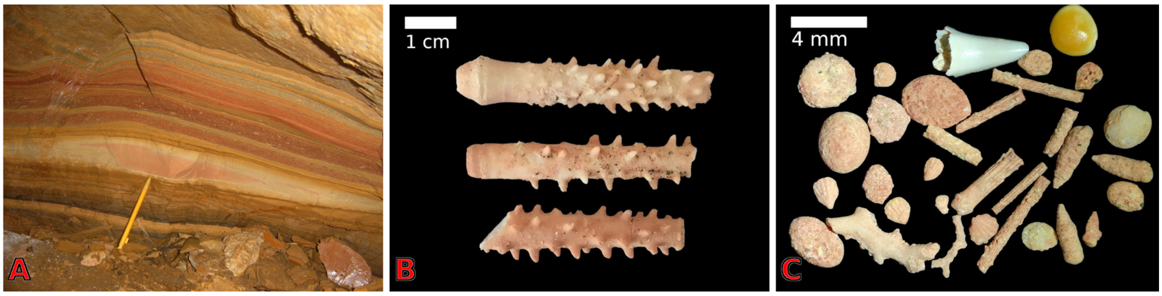

Fig. 8. Main fill at Grotta Tirapelle and related fossils. **A:** Layers of fossiliferous red and green arenites overlapping ochre laminations; **B:** *Prionocidaris* spines, commonly found in the red arenite; **C:** Fossil assemblage in the red arenite. From the top, clockwise: fish teeth; reworked nummulitid; well preserved benthic foraminifera; echinoid spines; brachiopod shells; echinoid tests.

Grotta Desora

Cave location: Verona, Via Castello S. Felice, fifth hairpin turn, WGS84 coordinates N 45.453504, E 11.004247, altitude of entrance 125 m (Fig. 9A, B); lithology: lower banks of Priabona Formation (early Priabonian); inventory number: 8677-V-VR.

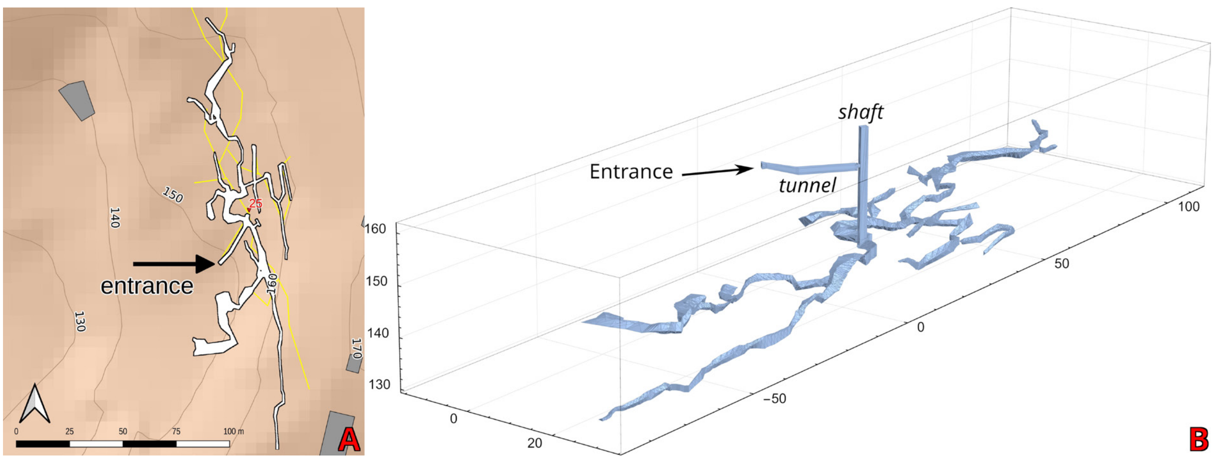

Fig. 9. Grotta Desora. **A:** Cave plan and location; **B:** Three-dimensional map of Grotta Desora (including the artificial shaft and entrance tunnel), highlighting the limited vertical development of the cave. X and Y axes show distances in m from the entrance; Z axis shows the elevation in meters above sea level.

Morphology

Unlike the other caves, morphologies at Grotta Desora are not always recognizable. The cave was subject to several collapses that apparently occurred after the ochre excavation, due to the mechanical properties of the host rock which is relatively weak. We witnessed one such collapse during our surveys.

More collapses were caused by the presence of high-angle faults at passage sides (Fig. 10A). Moreover, some branches were not excavated as they contained "useless" fills (i.e., not ochre). As a result, morphologies can only be observed in some areas.

The entrance is a 16 m deep artificial shaft that connects to the main passage. The cave plan shows a weakly defined branchwork pattern; a North-South orientation of the passages is clearly identifiable (see also Supplementary Fig. S5, Supplementary Fig. S6, and Supplementary Table S3). Passages are 4 m high at most.

A section near the entrance and the southern branch of the cave (Fig. 10B) has the same morphology (ceiling channel, facets, and vadose canyon) that we described earlier at Grotta Tirapelle; non-anastomotic, deeply incised ceiling channels are also present. Other passages are vadose slots (Fig. 10C), which we observed only in this cave. Paragenetic modifications like wall notches and pendants are widespread.

Sediments and fills

In this cave, several types of fills have been observed; some of them have not been examined to assess the presence of fossil remains.

The most significant fill is visible for over 7 m in the northern branch (Fig. 10D). It is up to 120 cm thick and consists of two coarse layers sandwiched in between ochre layers. The lower fill is a well cemented, white bioclastic limestone with hints of lamination; the upper layer is made of alternating levels of fossiliferous marl and ochraceous silt, showing cross-lamination and ripple marks. This sediment also contains a siliciclastic fraction consisting of muscovite crystals.

The limestone layer contains thick spines of *Prionocidaris* sp. and an assemblage of Priabonian benthic foraminifera (*Assilina* sp., *Asterocyclina* sp., *Actinocyclina* sp., *Nummulites* sp. ex gr. *incrassatus*, *Discocyclina* sp., *Operculina* sp., *Fabiania* sp.; Gonzato et al., 2014).

The upper silty and marly fills contain small bivalves (*Ostrea* sp.), tiny echinoid spines, thick spines of *Prionocidaris* sp., benthic foraminifera (*Amphistegina* sp., *Bolivina* sp., *Dentalina* sp.), bryozoans, undetermined bone fragments and fish vertebrae, and leaves of terrestrial plants (Fig. 10E, 11A). A remarkable find is a caudal vertebra, which has been attributed to a dolphin (Fig. 11B). Overall, the fossil assemblages may be attributed to a littoral or neritic environment.

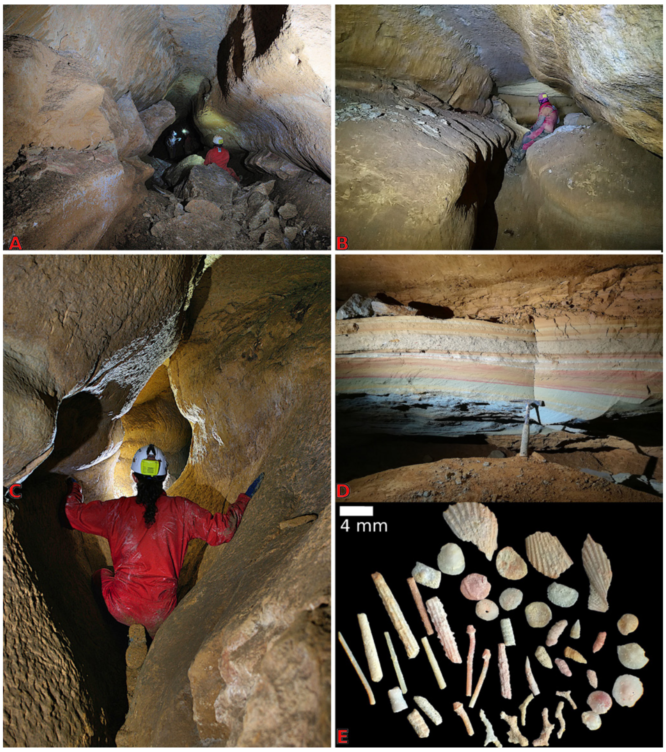

Fig. 10. Common morphologies and fossils at Grotta Desora. **A:** Main passage, heavily modified by subvertical faults; **B:** Passage with common morphology: flat roof with wide ceiling channel, lateral inclined facets, and short vadose entrenching; **C:** Vadose slot; **D:** Main fill at northern branch: fossiliferous limestone, marl, and silt sandwiched between ochre layers; **E:** Fossil assemblage in the fossiliferous layers. From the top, clockwise: bivalve shells (pectinids, *Ostrea* sp.), benthic foraminifera; bryozoans; echinoid spines and platelet.

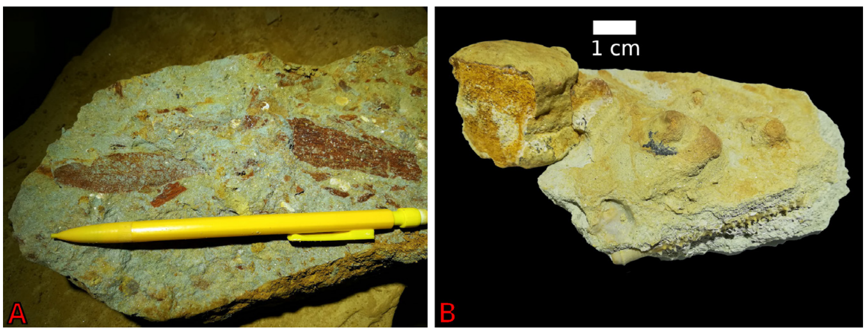

Fig. 11. Fossils at Grotta Desora. **A:** Leaf of terrestrial plant and vegetable fragments; **B:** Dolphin caudal vertebra and Prionocidaris

Grotta Colombare

Cave location: Verona, Via Castello S. Felice, within Parco delle Colombare; N 45.453548, E 11.007636, altitude of entrance 154 m (Fig. 12). Lithology: transitional boundary between upper *Calcari Nummulitici* (Bartonian) and lower Priabona Formation (Priabonian); inventory number: 8676-V-VR.

This is a very small cave (length is 85 m; for a quantitative analysis of survey data see Supplentary Figs. S7, S8, and Table S4) that might be a branch of the nearby Grotta DeliNpero that was detached by erosion. Several collapses make the morphologies barely recognizable; the only preserved passage has the same T-shaped morphology as the one observed in Grotta DeliNpero.

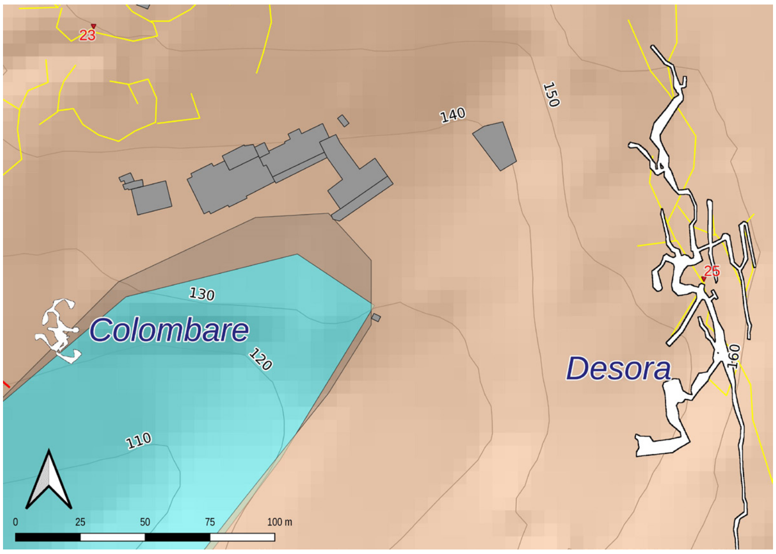

Fig. 12. Location and map of Grotta Colombare, near Grotta Desora.

In all passages of this short cave, a layer of carbonate-rich sandstone overlays an ochre fill; thickness varies from 5 to over 30 cm (Fig. 13A, B). The fill contains many tiny pebbles of quartz, flint and other rocks, in addition to crystals of biotite and muscovite (Fig. 13C). In thin section, numerous reworked bioclasts can be recognised: fragments of inoceramids, benthic foraminifera (*Nummulites*, maybe *Discocyclina*), oysters, barnacles, and red algae. Oysters and foraminifera are associated to glauconite.

Fossils in the sediment filling belong to different ages and environments. For example, inoceramids can be attributed to the Cretaceous, while *Nummulites* and *Discocyclina* are of Eocene age. Most bioclasts in sediments of Grotta Colombare are clearly reworked.

Fig. 13. Fills at Grotta Colombare. **A-B:** A 5-cm-thick layer of fossiliferous sandstone, overlaying a layer of brown ochre; **C:** Detail of the sandstone, showing quartz pebbles, muscovite crystals, and a pectinid fragment.

DISCUSSION

Origin and emplacement of the fills

It is essential to determine whether the cave fills originate from the host rocks, whose ages range from the late Bartonian (middle Eocene) to the early Priabonian (late Eocene). At Grotta DeliNpero, some thin layers of breccia embedded in ochre clearly originate from the erosion of the host rock. These fills consist of clasts of Eocene limestone containing *Nummulites*, *Discocyclina*, and fragments of bivalves; these are the same fossils, in the same lithology, which can be observed in the cave walls.

In all other cases, there is strong mismatch between the lithology and fossiliferous contents of fills and host rock. In particular, quartz, biotite, and muscovite are not found in Bartonian and Priabonian limestones and marls. The fossiliferous content is an important element of distinction. In all cases but one, in fact, some fossils in the fills can be attributed to the Miocene, while the host rock is Eocene.

At Grotta Desora, both the host rock and the fossils in the bioclastic limestone fill are of Priabonian age; this may suggest that the fill originates from the erosion of the host rock, but the fill at Grotta Desora may be a primary sediment as well. In fact, it is entirely bioclastic and does not contain clasts of host rock, as occurs in the breccia layers at Grotta DeliNpero. It has a different color and texture from the host rock. Many fossils that are abundant in the fill (bone fragments, fish vertebrae, echinoid spines) are not found in the host rock. Fossil markers of Oligocene/Miocene that are abundant in other fills have not been found in this fill. Eocene fossils such as the ubiquitous *Nummulites* are very well preserved and undamaged, and do not show the fragmentation and abrasion that are typical of transported or reworked fossils (Beavington-Penney, 2004). This fill could then be of Priabonian age, which would imply eogenetic karst. The dating of this fill may be corrected by the finding of fossils that are younger than the Priabonian, or by sedimentological evidence of a clastic origin.

The coarse-grained fills – those with Miocene fossils for sure, but maybe also those with Eocene fossils – represent littoral or neritic sediments that have been trapped and preserved in the caves and deposited episodically within soil material that was entering the cave through vertical fissures. Fossils included in the fills therefore provide an ante quem dating of the caves.

Processes that led to the emplacement of the fills are not fully clear. Alternating ochre and marine sediments at Grotta Tirapelle seem to suggest that both fills entered the caves from the surface; we hypothesize that storms or tsunami events made marine waters reach the shafts that normally washed ochre into the caves. In the case of the fill at Desora Cave, crossed lamination and ripple marks suggest a direct marine ingression (Fig. 14); in particular, the current seems to have transported the fills from S to N, i.e., inland from the paleo-coastline.

At Grotta Tirapelle, marine fills tend to seal the upper part of ceiling channels; this suggests that phreatic or epiphreatic conditions were caused by a sea level rise, which stranded the sediments in the cave. The middle Miocene transgression "drowned" the caves and ended their fossilization.

Fig. 14. Grotta Desora, northern branch: ripple marks in fine-grained arenitic fills.

Type of paleokarst

Identifying the type of karst that originated the caves at Torricelle Hills is a difficult problem, and only a small part of the paleokarst network has been examined. Nevertheless, we suggest that the set of available observations and data allows a consistent reconstruction.

Stratigraphic settings and palaeogeography

In the central Lessini "paleokarst belt" there are several examples of paleokarst caves and fissures filled by ochraceous sediments or, in some cases, filled by late-Eocene or Oligocene basalt (Gonzato et al., 2017).

The stratigraphic settings and the associated paleokarst provide strong evidence for subaerial emergence of this belt starting from the late Eocene. Adjacent areas to the east and west, where Oligocene deposits can be found, lack ochre-filled paleokarst phenomena. We can hypothesize that the "paleokarst belt" was an island or peninsula, whose southern edge roughly corresponded to Torricelle Hills. This area provides evidence for an early phase of emersion of the Lessini Shelf.

Cave patterns and morphologies

Cave patterns vary from anastomotic mazes (Grotta DeliNpero) to branchwork (Grotta Tirapelle, Grotta Desora). The origin of maze caves has been the subject of a long-standing debate (Palmer, 1975, 2011; Klimchouk et al., 2014).

Maze patterns, especially those with tectonic control, are often attributed to hypogenic speleogenesis (Klimchouk et al., 2014), but examining macro-morphological features is obviously not sufficient to draw such a conclusion for Grotta DeliNpero as well. Hypogene caves, in fact, possess a typical set of meso-morphology features (morphologic suite of rising flow; Klimchouk, 2009), none of which was found at Torricelle caves. Some of the missing features are, first of all, rather large passage dimensions; cave development in the vertical direction; rising chains of ceiling cupolas and arches; bubble trails; feeders; minerals and ore deposits, etc. (see also D'Angeli et al., 2018). While we cannot rule out the possibility of hypogenic speleogenesis altered by subsequent development, we find a coastal karst origin more likely.

Maze-like cave patterns are also common in coastal settings, such as Quintana Roo (Smart et al., 2006) or Bermuda (van Hengstum et al., 2011). The maze pattern of Grotta DeliNpero is very similar, albeit of smaller dimensions. The explored part of Grotta DeliNpero is probably only a subsection of a larger cave; in fact, other maze caves (now inaccessible) have been reported in the area (Zorzin & Latella, 2007). The N-S orientation of Grotta Desora and Grotta Tirapelle may also be approximately perpendicular to the paleo-coastline to the S, as shown by the geometry and sedimentological features of local Miocene outcrops (De Zanche et al., 1977).

The morphology of most cave passages implies that they started developing in phreatic conditions, at the water table or close to it, as indicated by flat ceilings and facets that suggest still or very slow water velocity (Fig. 15A). Several speleogenetic models have been developed to describe conduits of this type (Gripp, 1913; Reinboth, 1971; Kempe et al., 1975). Low-energy environments are required for the development of the convection currents (represented in Figure 15B) that are thought to originate facets (Kempe & Hartmann, 1977); the same holds for the sedimentation of very fine-grained materials that armor the conduit floor.

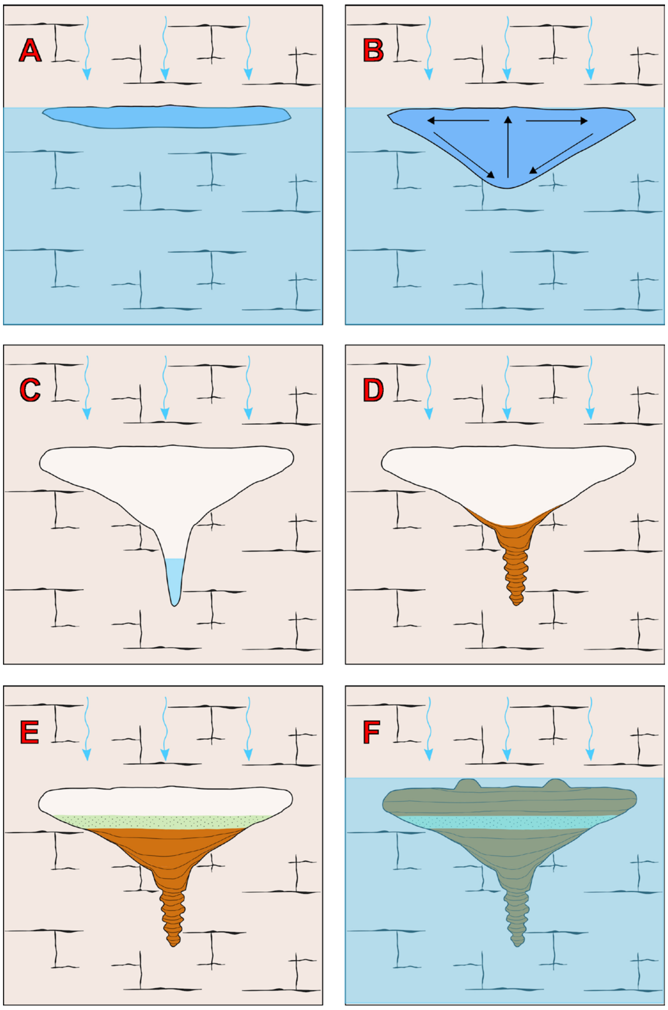

Fig. 15. Morphologic evolution of passages: **A:** Initial passage formation at the top of the freshwater lens; **B:** Development of convection currents and formation of wall facets; **C:** Lowering of the water table top and ensuing vadose entrenchment; **D:** Initial ochre build up and paragenetic wall modifications; **E:** Sedimentation of fossiliferous layers by marine ingressions; **F:** complete filling of passages, formation of ceiling channels, and final fossilization.

Conduits with facets have been described in hypogene carbonate caves (Bella & Osborne, 2008), in coastal caves in Yucatán and Mallorca (Smart et al., 2006; Gràcia et al., 2011; Ginés et al., 2014). In these caves, facets are developed only at stretches in some conduits, while they are predominant or nearly ubiquitous in Grotta DeliNpero. The presence of facets also in the other Torricelle caves suggests that low energy hydrodynamic conditions controlled the speleogenesis in the area until the final, paragenetic phase of network development. The lack of coarse continental sediments in the observed outcrops supports this interpretation.

The phreatic phase was followed by a vadose phase of development, probably triggered by tectonic uplift and/or eustatic sea level drop (as strongly indicated by the absence of Oligocene sediments) Morphologies produced during the vadose phase had a limited vertical development (Fig. 15C). The meandering of passages and the lack of a definite flow direction indicate a very low vertical gradient; this entails slow water currents, as testified by the lack of high-energy sediments. The overall 4-5° inclination that can be measured at Grotta DeliNpero corresponds to the local strike and dip of Eocene rocks – i.e., the cave was horizontal as it formed, and was tilted afterwards.

Ochre deposition caused paragenetic modifications of the passages (mostly, flat ceilings and wall notches; Fig. 15D); marine ingressions deposited fossiliferous layers (Fig. 15E). Finally, sediment accumulation led to the fossilization of the passages in phreatic or epiphreatic conditions, as shown by the widespread ceiling channels and pendants (Fig. 15F).

Sediments and fills

Ochre, siliciclastic, and fossiliferous fills provide important information for the reconstruction of paleogeography and paleoclimate of the area; fossil assemblages in the fills can also provide opportunities for dating.

Lateritic soils form by subaerial weathering of the bedrock in warm and humid conditions, and are typical of tropical climates (Tardy, 1997), although not exclusively (Bourman et al., 2020). In the Lessini area, tropical conditions throughout the Eocene are demonstrated by the fossil record at Bolca (early Eocene; Papazzoni et al., 2005) and Avesa near Verona (middle-late Eocene; De Zanche & Sorbini, 1980). Further, middle to late Eocene lateritic paleosols are found in the eastern Lessini Mountains as the result of weathering of mafic volcanic rocks (Piccoli, 1966).

The pervasive presence of ochre in the fills, whose chemical composition is the same as lateritic soil, and paleontological evidence are a strong indication of tropical climate conditions, possibly during a lateritization event that occurred around 35 Ma ago (Retallack, 2010). Ochres would then be interpreted as soil colluvium, i.e., reworked lateritic soil. Fossiliferous fills characterized by neritic-littoral assemblages testify for the proximity to a coastal environment. We can therefore conclude that the Torricelle caves are a fossilized example of tropical karst that developed in coastal eogenetic conditions.

Fossiliferous fills are commonly found towards the top of the passages; sometimes they represent the topmost fill that seals ceiling channels. This seems revelatory of ongoing “drowning” of the karst; littoral sediments were washed into the caves before the final phase of marine transgression occurred in the middle Miocene. The dating of the lower fill at Grotta Desora, if correct, would testify for an isolated episode of emersion and eogenetic/syngenetic karstification during the late Eocene. Syngenetic karst is a term coined by Jennings (1968) for karst features, including caves, that form within a soft, porous, soluble sediment at the same time as it is being cemented into a rock; the model has been further developed by Grimes (2006). Thus, speleogenesis and lithogenesis are concurrent. Eogenetic/syngenetic karstification is consistent with the paleontological evidence of dry land in the area starting from the middle Eocene (palm trees and turtles at Avesa, near Torricelle Hills; De Zanche & Sorbini, 1980).

Siliciclastic fills pose an interesting problem concerning the provenance of mineral clasts and rock fragments. Muscovite and part of the quartz probably originated from the erosion of the metamorphic crystalline basement that currently outcrops 35 km

NE from Torricelle, in the Recoaro area (Antonelli et al., 1990). The closest source of biotite and quartz upstream of Torricelle is the porphyry of the Gruppo Vulcanico Atesino (Avanzini et al., 2010), some 90 km N from Torricelle. The siliciclastic fills therefore may testify to the denudation of these areas, their erosion, and the transportation of resulting sediments.

Drawing a comparison with the sediment-filled Bermuda caves described by van Hengstum et al. (2011) highlights several differences. They describe sediments of vadose, littoral, anchialine, and submarine environments in caves that have a connection to the open sea. In contrast, Torricelle caves only contain two types of sediments (vadose and littoral); besides, they apparently did not have an entrance towards the sea, except for Grotta Desora.

Mechanisms of marine sediment emplacement are not resolved. We speculate that sediments entered caves during catastrophic events, such as hurricanes or tsunamis, that brought marine sediments at the entrances of the same crevices that washed lateritic soils in the caves. This could explain alternating levels of ochre and marine sediments at Grotta Tirapelle.

Lack of speleothems

Speleothems are completely absent in all ochre caves. The absence of speleothems is not the result of excavation: we never observed stalactite studs or flowstone fragments. Although we find this situation to be quite a peculiar feature of these caves, we have no explanation for the lack of speleothems. There is no vadose percolation into the cave today and no vadose speleothems forming today. There is no past evidence of vadose speleothem development. Hence, we might assume that the vadose conditions of today are inherited from previous conditions.

Speleogenesis of Torricelle caves

Paleokarst phenomena at Torricelle Hills are complex; besides, further study is needed, as only a limited part of the paleokarst network has been explored. Nevertheless, we believe that our observations can provide a coherent interpretation within the Carbonate Island Karst Model (Mylroie & Carew, 1995; Mylroie & Mylroie, 2007). This model describes eogenetic karst that develops in highly porous and permeable limestones, due to undersaturation of groundwater in the mixing zone, where the freshwater lens gets in contact with marine groundwaters. In small islands, diffuse flow is predominant; flank margin caves thus develop preferentially at the edge of the freshwater lens near the coastline. In larger islands, diffuse flow becomes inefficient and is replaced by conduit flow (Larson & Mylroie, 2018).

Torricelle caves testify to the subaerial exposure of the southern edge of the Lessini Shelf during a phase of marine regression. The cave development started in phreatic conditions at the top of the freshwater lens in a flat carbonate island or peninsula approximately 30 km wide, and further developed within short distance from the coastline, which allowed marine sediments to be washed into the caves occasionally. Features of the caves at Torricelle indicate that they formed by conduit flow development, rather than diffuse flow. Flank margin caves probably existed at the coastline, but none has survived erosion.

The island or peninsula was probably connected to the mainland at the northern edge of the Lessini Shelf, near Trento. The area had a low elevation and relatively high porosity and permeability, which constrained the vertical dimensions of the freshwater lens and, therefore, of the caves. Eustatic sea level drop established vadose conditions, while subsequent sea level highstand and Miocene transgression lead to epiphreatic conditions, and eventually to the drowning of the caves. The Shell Branch at Grotta Tirapelle (Fig. 7B) was later rejuvenated and had an additional phase of vadose development.

Karstification was probably enhanced by the decay of the organic matter contained in lateritic soils, which also altered the cave morphologies through paragenetic modifications. Parts of the island or peninsula that were farther away from the coastline developed the ochre-filled telogenetic paleokarst in the central Lessini Mountains (e.g., Ponte di Veja, S. Giorgio di Valpolicella; Cavallo et al., 2015). In this paleokarst, the lack of marine sediments in the ochre fills may indicate that the Miocene transgression only affected the southern edge of the Lessini Shelf.

CONCLUSIONS

In this paper, we have described a set of paleokarst caves, fossilized by ochre, located at Torricelle Hills (Verona, Italy). These “ochre caves” that became accessible due to the excavation of the ochre infills, are developed in middle-late Eocene limestone; the area is close to the southern edge of a Cenozoic carbonate platform called Lessini Shelf. In addition to ochre, siliciclastic and calcarenite fossiliferous infills are also found.

The ochre fills consist mostly of iron oxides and iron hydrated oxides, and we interpret this material as reworked laterite soils. In the past, it has been suggested that their origin should be related to the dissolution of the enclosing limestone. Considering the marked geochemical mismatch between the host rocks and the ochre, we suggest that the ochre primary source were local basaltic rocks, including some entrained by aeolian transport from volcanic areas to the East. Ochre was the product of subaerial weathering of this volcanic material in warm and wet conditions and was washed into the caves leading to their fossilization.

In each cave, branches develop along a single plane originating a branching or maze-like anastomotic pattern; in one case, water flow direction could be identified. Cave morphologies show a succession of phreatic, vadose, and epiphreatic phases of development. Paragenetic features such as wall notches can be attributed to the ochre infills, and are widespread in all caves. Well-developed wall facets indicate very slow water circulation. Polyphase development, including a post-Miocene vadose phase, can be identified at Grotta Tirapelle.

Morphologies, cave plans, and the presence of infills containing neritic fossil assemblages suggest that these caves developed in eogenetic limestones in a coastal environment. The caves drained a section of the Lessini Shelf that was above sea level between part of the Oligocene (the time span is unknown) and the middle Miocene. Similarities can be drawn between the ochre caves and the conduit caves that develop in eogenetic rocks in large islands.

Siliciclastic and calcarenite infills contain terrigenous clasts (quartz, biotite, muscovite, etc.) that are extraneous to the carbonate-only geology of the area. In the case of part of the quartz and mica, provenance could be related to the erosion of the crystalline basement that currently outcrops to the north of the area. Fossil assemblages in calcarenite infills contain echinoids, molluscs, brachiopods, bryozoans, benthic foraminifera, fish teeth, and more; overall, the assemblages indicate a littoral environment.

Fossil assemblages were dated to the late Eocene (Grotta Desora) and to the middle Miocene (Grotta Tirapelle, possibly Grotta DeliNpero) (Gonzato et al., 2014).

Future work will focus on the petrography and paleontology of the infills, on the comparison with the ochre-filled paleokarst in the central Lessini Mountains, and on the rediscovery (if possible) of other ochre internas in the Torricelle area.

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Authorship statement: GG and GR designed and directed the study; GG, GR and RC surveyed all caves and collected data; GG and GR analyzed and interpreted the data; EB and NP analyzed the fills at Grotta Tirapelle and Grotta Colombare; RC carried out statistical analyses; GG wrote the first drafts of the manuscript; all authors reviewed and edited the final version of the manuscript.

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