

Palynological evidence of Middle Pleistocene palaeoenvironmental changes from the 'Buca dell'Onice' flowstone (Alpi Apuane, Central Italy)

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Funding information

Fondi di Ricerca Ateneo - Università degli Studi di Firenze, Grant/Award Number: 2010-2015

Abstract

Buca dell'Onice di Monte Girello is a small cave located in the Alpi Apuane (central Italy). It preserves an exceptionally thick flowstone deposited intermittently during the Middle Pleistocene. Two main depositional cycles, separated by a physical discontinuity, have been recognised and described. This discontinuity and the top surface of the flowstone attest to two main phases of interrupted growth related to palaeoenvironmental and palaeoclimate changes. Pilot palynological investigations support the existence of such changes. Despite the high number of barren pollen samples and the overall very low concentration of pollen grains per gram of sediment, palynology furnishes some interesting insights especially regarding floral composition, vegetation cover and local to regional climate. The pollen record also contributes to the definition of the stratigraphic distribution of taxa no longer growing in this area (i.e. *Carya* and *Picea*). According to the pollen assemblage characteristic of arboreal vegetation cover, the flowstone was deposited predominantly during humid phases under both warm and cool climate conditions (interglacials/interstadials and at the end of interglacials). The warm and cool phases correspond, respectively, to increases of mixed thermophilous forest taxa and montane arboreal taxa. On the other hand, the pollen record does not show the major expansion of open vegetation associated with the coldest and driest conditions, which apparently fall at the main middle discontinuity and at the top interruption of the flowstone. Previous data permit changes in precipitation to be identified as one of the major limiting factors for the growth of this flowstone, probably in a period including MISs 13-10. The more significant lithological features of the flowstone as well as the vegetal and climate signatures suggest that its development principally represents a response to global events including teleconnections active between the Mediterranean and the Atlantic circulation, with minor contribution from local factors.

KEYWORDS

cave deposit, karst, late Quaternary, Mediterranean area, pollen, speleothems

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1 | INTRODUCTION

Non-marine carbonates are potential archives for recording natural environmental variations (climate, hydrology, tectonics) and anthropogenic impact, thanks to their sedimentological, petrographic, palaeontological and geochemical-isotopic features, which reflect the depositional environment including the chemical and physical properties of the waters from which they originate. Among them, speleothems (stalagmites, stalactites and flowstones) are secondary carbonate deposits that form in caves from percolating waters rich in CaCO_3 as calcite (or aragonite) precipitates, following CO_2 -outgassing (Ford & Williams, 2007). Their analysis, especially on regular stalagmites fed from a point-source (single drip site), has revealed a clear correlation of geochemical records with other climate proxies collected in distinct natural archives (e.g. marine oxygen isotope and terrestrial pollen records: Baker et al., 1993; Budsky et al., 2019; Moreno et al., 2014; Regattieri et al., 2012, 2016; Zanchetta et al., 2007, 2014). Flowstones are a common speleothem in caves, associated with calcite precipitation from seepage water in the form of well-layered deposits covering different surfaces (e.g. floors or gently dipping walls; White, 2004). Despite their complex morphology and growth dynamics compared to stalagmites (they originate from multiple drip sites or laminar flow of percolating waters; Baker & Smart, 1995), flowstones are potentially important as palaeoenvironmental archives (Baker et al., 1996; Demény et al., 2019; Drysdale et al., 2006). They mainly occur in relict dewatered caves or caves which are only occasionally active. In some conditions, calcite precipitation can capture detrital or biological particles introduced by percolating or stream waters. Pollen can also occur as an accessory component of flowstones, often accompanied by fine sediments (McGarry & Caseldine, 2004). Palynology, which is widely used in the study of marine and, especially, continental deposits (e.g. marsh, lake, peat and soil sediments) has historically been less frequently applied to the study of terrestrial carbonates. The latter, in fact, were considered not optimal because of their generally low palynomorphs content, due to both ineffective pollen transport mechanisms and features of the depositional environment, including the frequent occurrence of diagenesis. However, the increasing number of palynological studies demonstrated, despite the complex taphonomic interpretation, the possibility of detecting a climate/environmental signal by recovering palynomorphs from the different terrestrial carbonate deposits. McGarry and Caseldine (2004, and references therein) clarified the role of palynology in the analysis of cave deposits and especially speleothems. In their review they confirm the potential of this natural archive to extract, in sufficient quantities, well-preserved palynomorphs, which are representative of contemporary vegetation on the surface permitting reconstruction of palaeovegetation. Further studies on Quaternary terrestrial carbonates, including travertine and calcareous tufa

(Bertini et al., 2014; Carrión et al., 1999, 2009; Caseldine et al., 2008; Festi et al., 2016; Matley et al., 2020; Ricci, 2011; Ricci et al., 2015; Tagliasacchi & Kayseri-Özer, 2020; Toker et al., 2015), provided similar evidence reducing previous alleged biases and frequent misunderstandings regarding this peculiar natural archive. Glacials/stadials and/or interglacials/interstadials were traced by pollen records which sometimes provided unique information on both the vegetal landscape and climate parameters (e.g. T and P) as well as the depositional context. The possibility to reconstruct, by pollen analyses, the rainfall amount and its seasonal distribution, that is, a key parameter in the formation of non-marine carbonate, needs to be especially highlighted. Accordingly, palynology appears to provide: (a) a unique record characterising the climate and other environmental conditions during deposition of thermogene travertines and (b) an effective contribution for environmental reconstructions in speleothems integrating high-resolution geochemical investigations. Finally, the potential of palynology in the study of Quaternary terrestrial carbonates is also enhanced by the fact that they can be accurately dated radiometrically, producing a reliable geochronology for the climate proxy records they contain, including the geochemical ones.

The case study presented here concerns a Middle Pleistocene flowstone located in an easily accessible cave, the 'Buca dell'Onice di Monte Girello', in the Alpi Apuane karst area (central Italy; Figure 1). This cave is a significant site for the exceptional thickness of its flowstone (at least 3.5 m), which is also well-exposed on a vertical section due to the mining of large calcite blocks for ornamental use (Piccini et al., 2003). It is one of many caves in the Alpi Apuane (e.g. Antro del Corchia, Grotta della Renella, Tana che Urla) where well-preserved speleothems play an important role in reconstructing late Quaternary palaeoclimate changes by providing several dateable levels and high-resolution geochemical data (Bajo et al., 2020; Drysdale et al., 2004, 2006, 2009; Isola et al., 2019; Piccini et al., 2003; Regattieri et al., 2016).

The main aim of this study was to verify, by a pilot research project, the application of palynology to the study of the flowstone for palaeoenvironmental and palaeoclimate purposes. The possibility to constrain local to regional flora and vegetation, and to develop inferences on climate parameters, especially precipitation, during this key time interval is of major interest, especially because of upcoming geochemical investigations and dating.

2 | STUDY SITE

2.1 | Description of the cave

Buca dell'Onice di Monte Girello (BOMG) is located in the Frigido River Basin, on the seaward side of the Alpi Apuane region (north-west Tuscany) (Figure 1) and was registered in

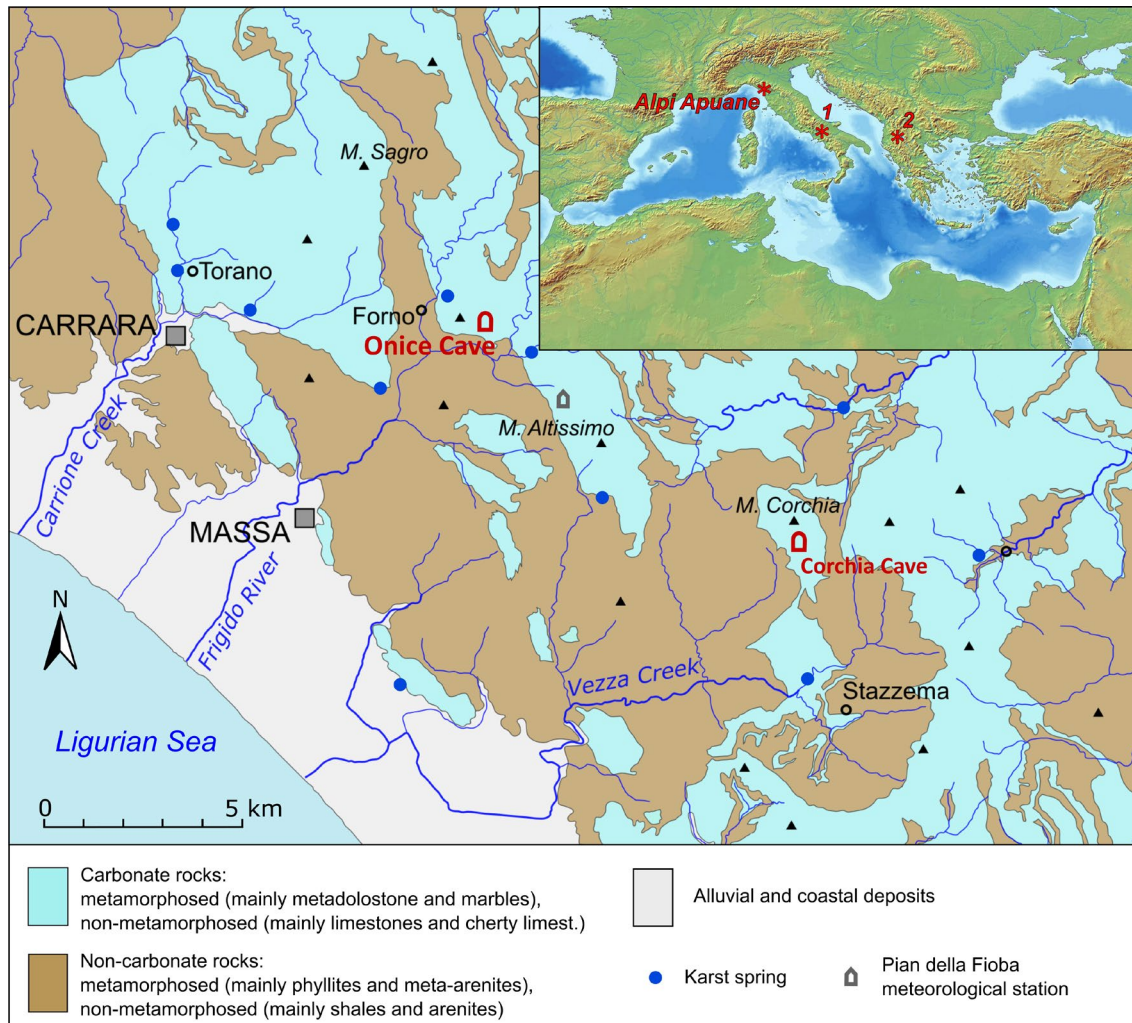


FIGURE 1 Geological sketch map of north-western Alpi Apuane and its location in the Mediterranean region (on the right) with respect to other palynological records cited in the text (1 – Boiano, 2 – Ohrid Lake). ‘Buca dell’Onice di Monte Girello’ (Onice cave) is in the Frigido River Basin close to the geological contact between Mesozoic carbonate formations and Palaeozoic basement

1967 (and later updates in 1998) in the Caves Census of the Tuscany Region with the code number 334 T/MS. The cave consists of an inclined, large conduit, 85 m long, 35 m deep and 7–8 m wide in its largest cross-section, carved into the Upper Triassic meta-dolostones (Grezzoni Formation) of the Apuane metamorphic unit. Its natural entrance opens at an altitude of 570 m a. s. l. on the southern side of Mt. Girello, while two lateral artificial tunnels intercept the cave at lower altitude (Figure 2). Conduit morphology supports a phreatic origin as part of a relict conduit system which fed an ancient karst spring now completely dismantled by slope erosion (Piccini et al., 2003). After the dewatering phase, due to the incision of the Frigido valley and the lowering of the local base level, the cave experienced a long phase during which seepage waters caused the deposition of a huge flowstone on the floor of the conduit. The flowstone consists of several calcareous layers characterised by millimetre to centimetre light and dark growth bands. The exceptional volume of the flowstone, and the relatively easy access to the cave, encouraged the quarrying

activity which continued into the 60s exposing a vertical face about 6 m wide and 3 m high (Figure 3). Several stalagmites, some of which are still occasionally active, grew on the top surface of the flowstone after its formation ceased. A small stalagmite which grew over the flowstone was dated at 290 (+85/–55) ka, whereas the upper portion of the flowstone is probably older than 350 ka (Piccini et al., 2003). In the lower part of the cave a 5–6 m thick, clastic deposit occurs. The sediment in-fill mainly consists of fine carbonate sand and was almost completely removed by successive erosion and during quarrying activity. Presently, sediments are only preserved on the north and east side walls of the lower chamber.

2.2 | Geological and geomorphological outline

The Alpi Apuane are a mainly calcareous mountain range, about 50 km long and 20 km wide, located in Tuscany and

directly facing the Ligurian Sea (Figure 1). The alpine-like landscape of this peculiar region is the result of differential

erosion on a complex structural setting. The very different response of lithologies in respect to weathering and denudation processes produced a rugged landscape where the highest ridges mainly consist of carbonate deposits while valleys and subdued areas are often made of siliciclastic deposits.

The whole massif consists of three main tectonic units that were over-thrusted, one upon the other, during the late Oligocene—early Miocene (Carmignani & Kligfield, 1990). Two of these units make up a single metamorphic complex of carbonate to terrigenous sediments, which has been overlapped by the third unit: the ‘Tuscan Nappe’. Metamorphism occurred during three tectonic phases, between 27 and 10 Ma (Kligfield et al., 1986). The lower part of the Apuane Unit consists of Carnian to Lower Jurassic carbonate shelf deposits, made up of metadolomite (‘Grezzoni’), dolomitic marble and marble (‘Marmo di Carrara’), overlain by pelagic siliceous limestone. In the late Miocene–Pliocene, extensional tectonics was responsible for the uplift of the Alpi Apuane massif along major peripheral faults with NW–SE and NE–SW strikes. Extensional tectonics promoted the formation of the surrounding coastal and intermontane basins (Magra and Serchio valleys) since the late Pliocene (Carmignani & Kligfield, 1990; Martini & Sagri, 1993).

Carbonate formations (meta-dolostones and marbles) host well-developed karst landforms and several caves, including

BUCA DELL'ONICE DI MONTE GIRELLO (T334)

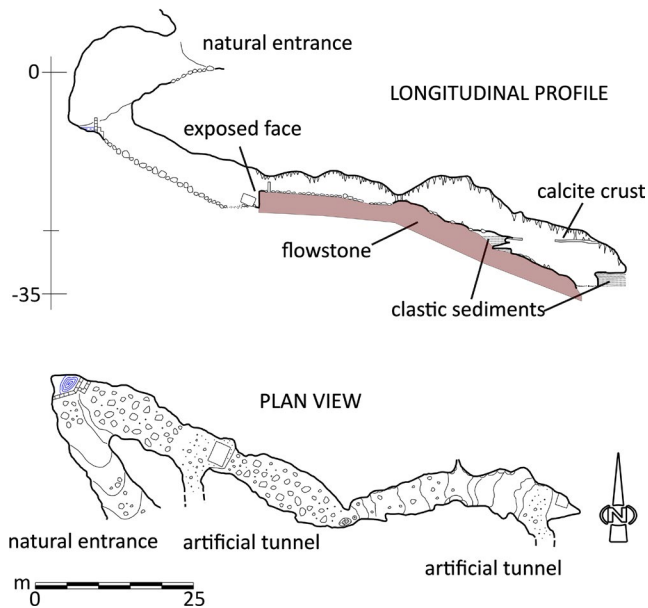
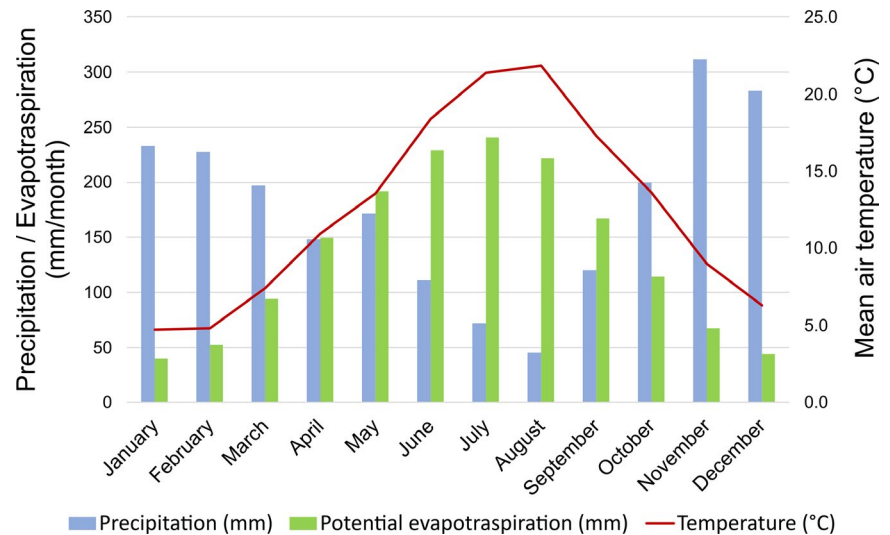


FIGURE 2 Longitudinal and plan view of BOMG with the location of sampled deposits (survey by Gruppo Speleologico Fiorentino, 1966: <http://www.speleotoscana.it/vista-grotta/?id=334>)



FIGURE 3 The vertical cut-face of the flowstone, exposed by mining activity of ‘Onice’ stone, allows a clear view of its stratigraphic and textural features (photo L. Piccini)

FIGURE 4 Climate parameters at Pian della Fioba meteorological station (860 m a.s.l.); from April to September potential evapotranspiration exceeds precipitation



some of the largest and deepest in Italy. Karst developed since the late Pliocene following the progressive exhumation of the carbonate sequences. Some major stages of karst development are related to tectonics and palaeo-hydrological readjustment of the river network (Piccini, 1998, 2011), whereas climate changes are mainly recorded by cave deposits (Isola et al., 2019).

2.3 | The modern climate, flora and vegetation

The Alpi Apuane massif exhibits a spatially heterogeneous climate pattern, especially related to the NW-SE oriented main watershed, which, from the narrow coastal plain, reaches in the space of a few kilometres an altitude of about 2,000 m (Monte Pisanino, 1,947 m). This mountain range represents an effective barrier against both the cold and dry northern winds, thus mitigating the climate of the Tyrrhenian side, and the more warm and humid winds coming from the sea. Therefore, the south-western side of the Alpi Apuane has a mild climate, with cool summers and not too harsh winters, while the north-east facing side has a more continental climate, with relatively short summers and cold winters, and even snow fall, persisting throughout the late spring in some high-altitude areas. The Alpi Apuane are one of the most rainy areas of the Italian Peninsula, with precipitation mainly occurring in autumn and spring (mean precipitation >2,500 mm/yr; Rapetti & Vittorini, 1995). At the highest altitudes, a prolonged dry season is absent due to frequent and often high-intensity, occasional summer rainfalls. Conversely, in the seaward low-altitude slopes, there is a typical Mediterranean climate characterised by a dry summer.

The close juxtaposition of areas with such different altitudes promotes a considerable variety of microclimates.

At Massa (65 m a.s.l.), about 9 km south-west of the study site (Figure 1) and located near the Tyrrhenian coast, the climate is warm-temperate (Csa) with a mean annual air temperature of *ca* 16.0°C and a mean annual precipitation of 1,151 mm (1981–2010 average: <http://www.lamma.rete.toscana.it/clima-e-energia/climatologia/clima-massa>). Only 2.7 km south of the study site, at Pian della Fioba (860 m a.s.l.), the mean annual air temperature is *ca* 12.4°C (2010–2020 average; <http://www.sir.toscana.it/>) and the mean annual precipitation reaches 2,120 mm (2010–2020 average; <http://www.sir.toscana.it/>). Despite the high rainfall, during summer potential evapotranspiration is higher than precipitation (Figure 4).

This climate, together with the peculiar geographical and geological features of the Alpi Apuane area, explain the occurrence of a very rich and diverse flora as well as its role as a refugium for numerous endemic species (Ferrarini, 1970). From the Tyrrhenian coastal zone towards the first significant relief, the vegetation cover is Mediterranean; *Quercus ilex*, *Myrtus communis*, *Pistacia terebinthus* and *Phillyrea latifolia* are largely present, especially in calcareous soil, up to about 300 m a.s.l.; *Pinus pinaster* extends up to about 600 m a.s.l., especially in siliceous soil. Inland, at higher altitudes, the *Quercocarpinetum* zone (e.g. *Ostrya carpinifolia*, *Quercus pubescens*, *Fraxinus ornus*) expands up to about 1,400 m a. s. l. when not replaced by man with vast chestnut woods. *Fagus sylvatica* thrives at higher altitudes, usually from 800–900 m up to 1,600–1,700 m a.s.l., but not on the Tyrrhenian side, where it is less extensive (1,200–1,400 m). The highest arid areas of siliceous soils host high-altitude heathlands taxa, whereas the calcareous soils are dominated by a sparse and discontinuous vegetation cover characterised by numerous herbaceous species that live on the rocky walls, mostly non-graminoid grasses, bushes and shrubs (casomphilous vegetation).

3 | MATERIALS AND METHODS

The sampled flowstone outcrops about 50 m from the upper natural entrance of the cave as a vertical face, 3.2 m high, which allows good sight of the internal stratigraphy. It was photographed, measured and described by direct field observations. The deposit of fine detrital sediments occurs in the lowest part of the cave and originally had to cover the lower and more inclined section of the flowstone. Sediments are exposed on a vertical section, about 5 m high, preserved on the walls of the inferior chamber of the cave (Figure 2).

Both the flowstone and the clastic deposit were sampled for palynological analyses. Flowstone samples were extracted with hammer and chisel from the large slab left in front of the vertical cut, and there abandoned after the end of quarrying activity, to preserve the integrity of the in-situ outcrop. Nine

samples of about 100 g (ONC10, ONC15, ONC20, ONC33L, ONC138, ONC147, ONC160, ONC170, ONC320) were collected from the calcite flowstone: the sample-codes indicate the mean distance in centimetres of the sample from the top surface of the flowstone, measured on its central section. Three samples (ONS 1, ONS A and ONS B) were collected from the clastic deposit that outcrops in the lower part of the cave at different heights.

All samples were submitted to physical–chemical procedures at the Palynological Laboratory of the Department of Earth Sciences (University of Florence, Italy). Flowstone samples and clastic sediments were prepared following procedures previously described in Ricci (2011) and Bertini et al. (2014). After extracting and weighing about 25–32 g and 73–96 g from clastic and flowstone samples, respectively, a *Lycopodium* tablet was added to each sample before chemical

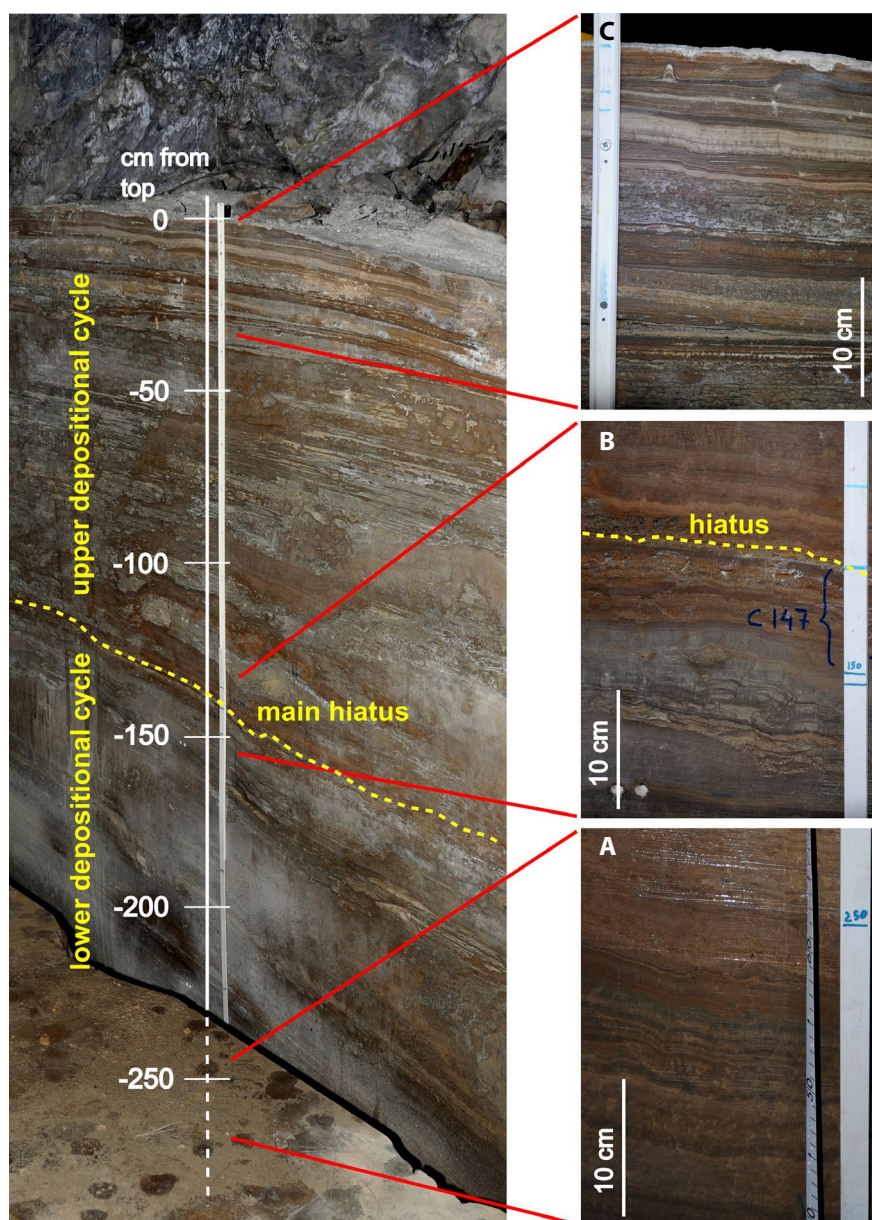


FIGURE 5 Photographic view of the middle-upper portion of the BOMG flowstone: (A) a part of the lower cycle showing a regularly laminated structure characterised by layers of different colours; (B) the main discontinuity occurring at 1.43 cm from top divides the deposit into two main portions with different textural characteristics; (C) the upper portion of the second cycle shows a well-laminated structure with layers of different and high-contrast colours according to their different composition and texture (photos M. Massini)

treatment to calculate the pollen concentration (grains/g). All samples were submitted to the following sequential chemical treatment: HCl to dissolve calcium carbonate, HF to dissolve the residual silicates and HCl in a warm bath to dissolve fluorosilicates. Pollen grains were then released from the sediment by using a heavy liquid (ZnCl_2 , density 2) and, finally, the residue was washed and sieved (at $10\ \mu\text{m}$) in an ultrasonic bath. Residues were preserved in glycerine and mounted on mobile slides.

Pollen grains were counted using a light microscope (NIKON 80i) at either $\times 500$ or $\times 1,000$ magnification. Several pollen atlases were used to aid pollen identification (Reille, 1992, 1995). A percentage pollen diagram was plotted using Pollen® (Bertini et al., 1992). In the summary pollen diagram, the different taxa were grouped into seven different ecological groups. (a) Temperate broad-leaved deciduous forest taxa (e.g. deciduous *Quercus*, *Carpinus*, *Tilia*, *Ulmus*), generally indicative of a warm temperate climate; (b) Mediterranean taxa (e.g. *Olea* and *Q. ilex*), xerophilous evergreen plants typical of Mediterranean regions characterised by a mild winter and a dry summer. (c) *Abies*, *Picea* and *Fagus*, cold-temperate montane climate taxa. (d) *Pinus* and other ‘saccatae’ indeterminate Pinaceae; this group includes species with different ecological and climate requirements. (e) Other arboreal plants (AP) (e.g. Cupressaceae, *Alnus*), including arboreal taxa possibly related to local edaphic conditions and not indicative of a specific climate. (f) Steppe taxa (*Artemisia*), with acme phases often associated with glacial conditions. (g) Other non-arboreal plants (NAP), including cosmopolitan non-arboreal taxa generally indicative of open environments and hydrophytes (e.g. Poaceae, Asteraceae, *Plantago*, Cyperaceae).

4 | RESULTS

4.1 | Stratigraphic features of the flowstone and clastic sediments

Despite the intense extraction of calcite blocks and concomitant severe damage, the BOMG is still a well-decorated cave in its middle-lower part where the flowstone is preserved. Conversely, the upper portion of the flowstone, with an estimated volume of at least $200\ \text{m}^3$, was completely removed by quarrying. Two main depositional cycles are well visible in the exposed face of the flowstone. The lower cycle, which is massive and uniformly laminated, is more than 1.7 m thick although the base is obscured. It displays a regular banding with alternating light and dark brown layers in the lowest part (Figure 5A). Upward, the deposit is progressively enriched in fine carbonate sands which often fill small pockets. A hiatus occurs at about 1.43 m from the top (Figure 5B). It represents a significant interruption of the flowstone growth and it is

marked by a thin sandy and friable crust, probably due to the deposition of detrital grains carried into the cave by high-energy infiltration events.

The upper depositional cycle is about 1.4 m thick in its central section, and it mainly consists of finely banded, brownish calcite. It has a less uniform texture than the lower cycle and displays several thin layers and small pockets of fine carbonate sands. Another textural change occurs about 30 cm below the top surface. Above this discontinuity, calcite deposition progressively become more regular and contains less detrital components (Figure 5C). The upper 10–12 cm shows strongly contrasting colour tonality. At 2–3 cm below the top surface, a 7–10 mm thick layer of transparent calcite occurs: it probably represents a phase of calcite precipitation formed by water dripping directly from the cave ceiling and not via laminar flow from the upper portion of the flowstone. There are several differently sized stalagmites above the flowstone indicating that once the laminar flow was interrupted, only local deposition due to point-site drips developed.

Detrital sediments, occurring in the lower part of the cave, mainly consist of fine sand and finely laminated silt, locally cemented (Figure 6). The coarser portions appear light grey and consist mainly of dolomite grains. The finer layers are darker and brown-reddish in colour, containing clay



FIGURE 6 The fine clastic sediments occupying the lower chamber of the BOMG cave (photo L. Piccini)

and other residual silicate minerals due to surface weathering processes. The deposit shows two major depositional cycles interrupted by a calcite crust about 10–15 cm thick. The lower cycle is about 2.3 m thick, continuous, and regularly laminated, whereas the upper cycle is about 3 m thick and shows some erosional surfaces related to different depositional sub-stages. This sediment fill extends laterally on the lower and steeper portion of the flowstone and covers some of the stalagmites that had grown on it. A calcite crust, some centimetres thick, covers the summit of the detrital sediments.

4.2 | Main floral and vegetational evidence from palynological analysis

Clastic samples (ONS 1, ONS A, ONS B) were all virtually barren in palynomorphs, having returned only sporadic pollen grains (Table 1); however, five of the nine carbonate samples (ONC10; ONC33L, ONC138, ONC170, ONC320) contain palynomorphs, ranging in concentration from *ca* 2 to 21 grains/g. The pollen grains are well-preserved, and they do not exhibit biological, chemical or mechanical degradation (Figure 7).

Palynoflora includes 37 pollen taxa from arboreal, shrubby and herbaceous plants (Data S1); selected single and grouped taxa are traced in Figure 8.

ONC 320: Arboreal plants dominate the assemblages. *Pinus* is the most abundant taxon (67.5%). It is followed by deciduous *Quercus* (12.5%), *Q. ilex* (evergreen) (7.5%),

Fagus (5%) and *Abies* (2.5%). Among the few herbaceous plants *Artemisia* is present (<2.5%) along with *Plantago*. Pollen concentration is *ca* 3 grains/g.

ONC 170: Arboreal plants are always dominant with respect to the non-arboreal ones. *Pinus* remains the most abundant taxon (*ca* 51%) with a considerable increase in *Abies* which here reaches about 30%. Deciduous *Quercus* (about 6%) as well as *Q. ilex* (3.5%) are considerably reduced. On the other hand, *Carpinus*, *Olea* and *Carya*, although rare, are part of the arboreal assemblage. Herbaceous plants are represented by Asteraceae Cichorioideae (*ca* 3%), Poaceae (*ca* 2%) and by isolated pollen of Campanulaceae, Amaranthaceae, *Rumex* and Scrophulariaceae. Relatively high pollen concentrations (i.e. 21 grains/g) are reached in this sample.

ONC 138: The percentage of herbaceous plants increases from this sample, settling on values around 40%. However, trees are still dominant. *Pinus* suffers an additional decrease, falling to 29%, whereas among angiosperms, *Q. ilex* exhibits a strong increase (21.4%). The deciduous *Quercus* (9%) and Cupressaceae (1.8%) follow in terms of decreasing abundance. Among the herbs, Poaceae (16%) dominate, followed by Cyperaceae (11%), among the hydrophytes. Other non-arboreal taxa, each contributing around 1.8%, are *Artemisia*, Asteraceae, Cichorioideae, Brassicaceae, Scrophulariaceae and Rosaceae. Pollen concentration is 6 grains/g.

ONC 33L: A significant increase in deciduous *Quercus* (43%) parallels an overall decrease in herbaceous plants in this sample. *Quercus ilex* stays quite high (20%) and *Olea* reappears (3%). *Pinus* values decrease to 17%. Cupressaceae increase up to 7%. Few taxa have been recorded among herbaceous plants, that is, Poaceae (7%) and Rosaceae (3%). The lowest relative pollen concentrations (i.e. *ca* 2 grains/g) were recorded in this level.

ONC 10: Non-arboreal plants increase considerably, exceeding 40%. They are mainly represented by Poaceae (*ca* 12%), *Buxus* (8%) and Asteraceae Asteroideae (6%). Then, in decreasing abundance, follow *Artemisia*, *Hedera* and Cyperaceae (*ca* 2%) as well as Asteraceae, Cichorioideae, Caryophyllaceae, Amaranthaceae, Ericaceae, *Galium*, Papaveraceae, *Plantago*, Valerianaceae and *Phragmites* (*ca* 1% each). Among trees, quite still well-represented, *Fagus* and *Alnus* are the dominant taxa (13% and 12%, respectively). They are followed in abundance by deciduous *Quercus* (7%), *Picea* (6%), *Tilia* (3.5%), *Abies*, *Acer* and *Carpinus* (all the last three at *ca* 2%) then Pinaceae, *Ulmus*, *Pistacia* and Cupressaceae (at *ca* 1% each). Pollen concentration is 7 grains/g.

TABLE 1 Weight and pollen grain concentration of ONC and ONS samples at BOMG

Samples	Weight (g)	Pollen concentration (gr/g)	
		AP	AP + NAP
Flowstone			
ONC10	72.7	4.54	6.73
ONC15	81.1	—	—
ONC20	92.3	—	—
ONC33L	96.2	2.15	2.39
ONC138	95.0	3.80	6.07
ONC147	93.0	—	—
ONC160	92.9	—	—
ONC170	92.9	19.38	20.81
ONC320	94.3	2.50	2.64
Clastic sediment			
ONSB	32.3	—	—
ONSA	28.0	—	—
ONS1	25.0	—	—

Abbreviations: AP, arboreal plants; gr/g, pollen grains/g; NAP, non-arboreal plants.

5 | DISCUSSION

5.1 | Flowstone depositional features

The flowstone is characterised by different facies defined mainly on: different growth rates, the dynamics of the water

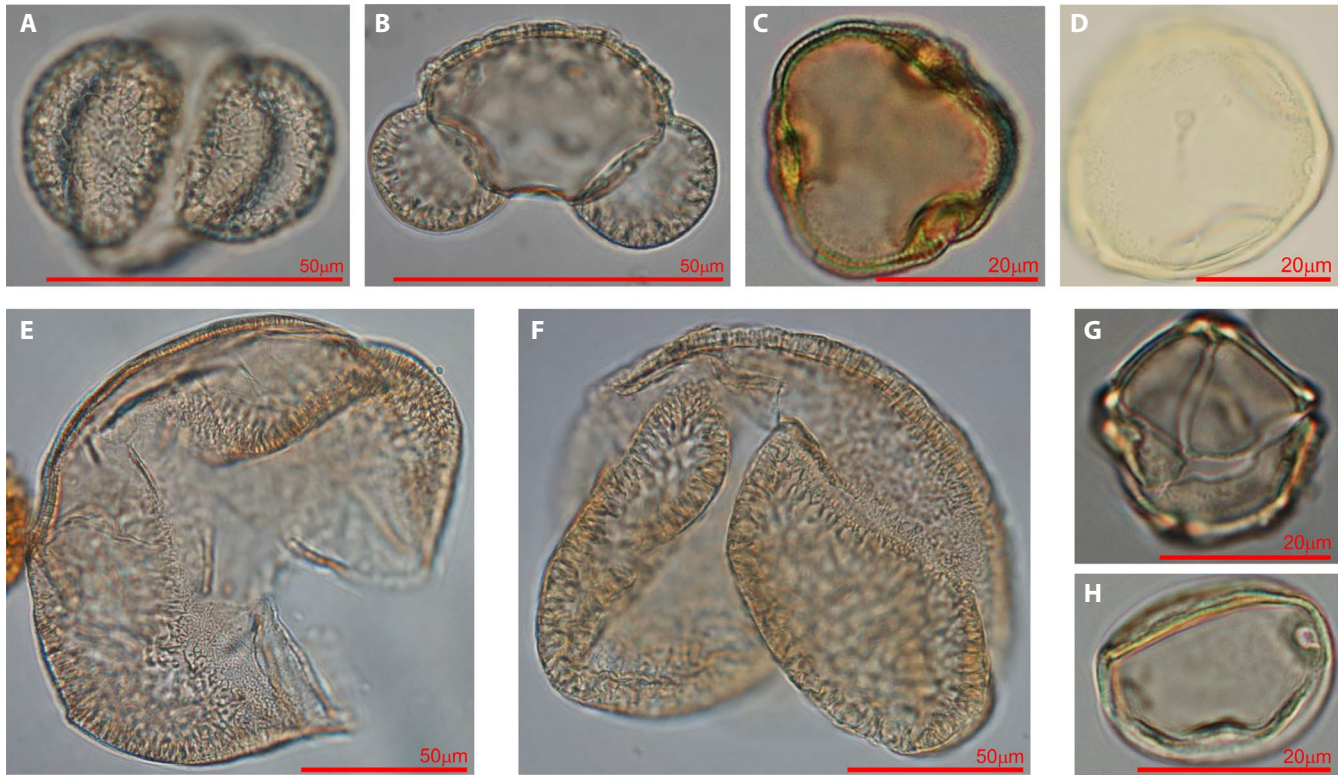


FIGURE 7 Pollen grains from BOMG flowstone. (A and B) *Pinus* spp., (C) *Tilia*, (D) *Carya*, (E) *Picea*, (F) *Abies*, (G) *Alnus*, (H) Poaceae

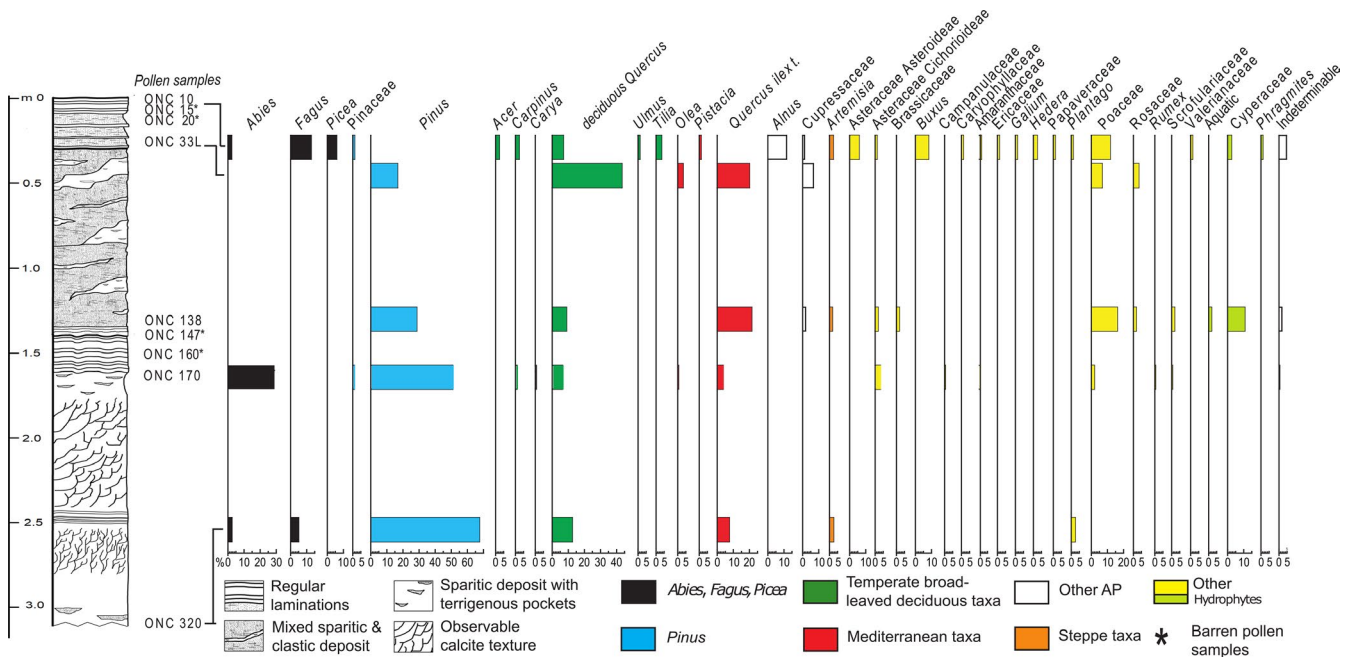


FIGURE 8 BOMG flowstone: semi-detailed pollen diagram with lithologic log on the left

flows and the different contributions of detrital materials. The main hiatus (Figure 5B), located about 1.45–1.40 m below its top surface, is associated with an important interruption in growth caused by an abrupt decrease in the water supply and/or to waters unsaturated in calcium carbonate. This interruption also corresponds to a facies change, which follows

modifications in the supply systems of the seepage waters. The lower part of the flowstone has more uniform characteristics, a more evident lamination, and only rare clastic components (Figure 5A). The upper part, on the contrary, has a less regular lamination and it is more disturbed by frequent recharge interruptions, identified by secondary discontinuities. In places,

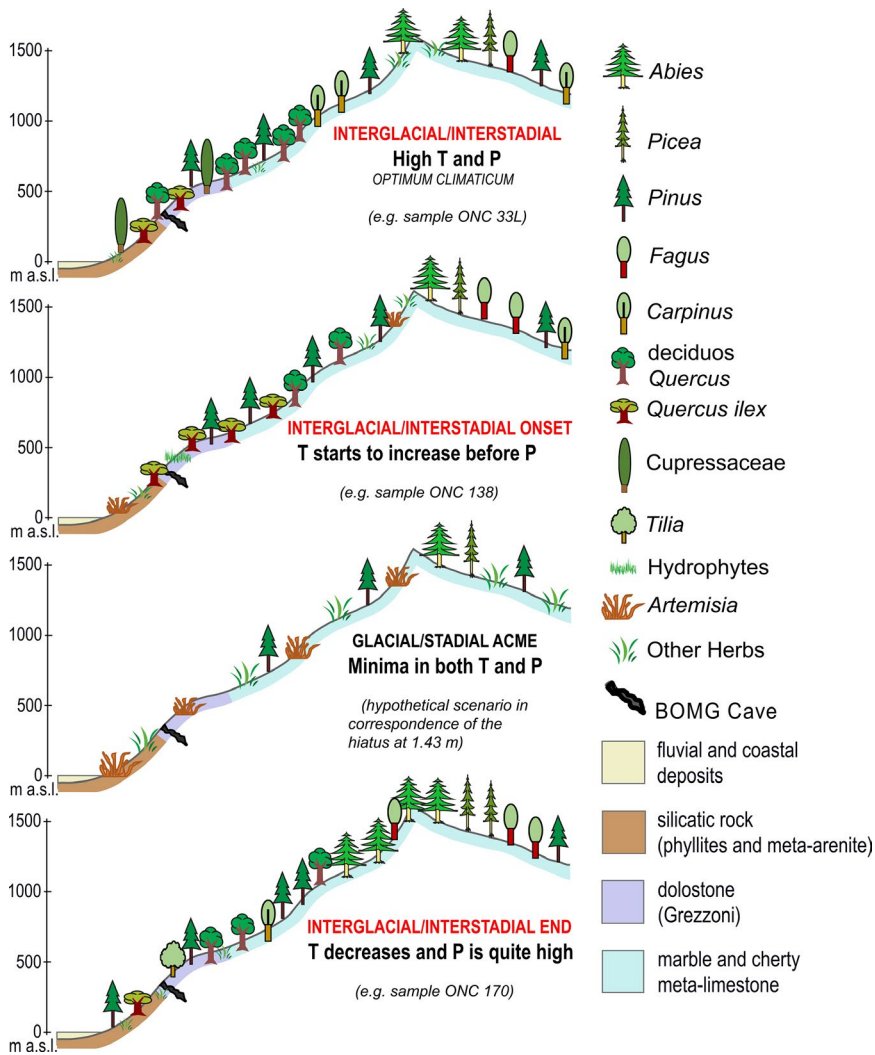


FIGURE 9 Schematic reconstruction summarising the dominant vegetation phases within the BOMG flowstone assuming that it formed from the Middle Pleistocene. The altitudinal profile ideally represents the morphology during flowstone deposition

there are textural changes probably due to a non-regular run-off, with areas affected by different flow rates and different precipitation conditions. In the uppermost part, between 0 and 33 cm from the top, the lamination is regular but characterised by colour contrasts more marked than in the underlying sections (Figure 5C). The top surface of the flowstone indicates an important growth reduction, which is probably due to the almost complete loss of the laminar flow supply. One possibility is that the water flow inside the cave reduced due to a change in the path of infiltrating waters previously feeding the flowstone. Another possibility is that a reduction of soil thickness, and the decrease of dissolution processes in the epikarst zone, promoted the change from supersaturated to undersaturated waters, even if the lack of clear corrosion rills on the flowstone surface seems to exclude it.

In a more general view, the texture and composition of the flowstone seem to indicate a progressive transition from a regular, and less climate-dependent, water supply to conditions characterised by frequent interruptions and occasional deposition of carbonate sands, produced by surface physical weathering and carried into the cave during storms. In

other words, these variations of textural facies are probably linked to a reduction in the thickness of the rock overlying the cave and therefore to a less continuous infiltration recharge, more affected by meteorological events and more sensitive to changes in the external environment, as well as to the contribution of detrital material produced by meteoric degradation processes and carried into the cave by infiltrating waters through karst cavities and not only through a network of fissures characterised by slow and regular flows.

5.2 | Pollen-based palaeoenvironmental and palaeoclimate changes

Pollen analysis provides information on the composition of the flora and vegetation as well as the main climate changes occurring during flowstone growth (Figures 8 and 9). Despite the typically complex history of cave systems, a knowledge of both the sedimentary depositional environment and the relationship between the palynomorphs within the cave and the external vegetation from which they are derived, allows

for quite a reliable interpretation of pollen diagrams. For this reason, all signatures useful for a proper and critical assessment of the pollen assemblages, such as the source area of the different palynomorphs (pollen catchment) as well as their abundance (including over-represented and under-represented phenomena), preservation, transport ways (e.g. waterborne and airborne components) and post-depositional history have been examined.

The BOMG flowstone contains well-preserved pollen grains where the concentration (Table 1) is quite close to that usually recovered in other speleothems (i.e. <1 and 30 pollen grains/g: Caseldine et al., 2008); moreover, reworked palynomorphs are absent. Considering the location of the flowstone inside the cave, the airborne pollen transport component, including traces of the local and regional vegetation of the area around the cave, was probably subordinated. However, redeposition of the airborne pollen which reaches the cave entrance, by water flowing down the walls of the cave onto the surface of the flowstone, is not excluded. A lack of information concerning the position and number (none, single, multiple) of cave entrances during the flowstone growth precludes further taphonomic inferences. Most of the pollen probably reached the site transported by water or together with sediments following surface runoff through swallets or sinkholes. In both cases, transport reflected a wide catchment area sourcing a regional pollen component. Transport by percolating/infiltrating water through bedrock/cave sediment probably also introduced pollen from the local vegetation (e.g. hydrophytes thriving in temporary ponds), growing above the cave, plus a small regional component.

All pollen spectra are dominated by arboreal pollen over non-arboreal (Figures 8 and 9). In particular, *Pinus*, deciduous *Quercus*, *Abies*, *Q. ilex* and *Fagus* reach quite high percentages. The basal pollen spectrum is strongly characterised by high *Pinus* pollen percentages although this genus progressively decreases in abundance upwards, disappearing by the top layer. The significant increase of *Abies*, a montane taxon, in ONC 170 along with quite a low occurrence of deciduous and evergreen oaks (compared to the lowest sample, ONC 320) apparently marks the beginning of a phase characterised by a decrease in temperature without major variations in humidity, probably foreshadowing a glacial/stadial stage. However, in the overlying sample (ONC 138), separated from ONC 170 by the sedimentary discontinuity placed 1.43 m from the top, there is no evidence of the glacial/stadial acme which is usually expressed in the pollen record of the Mediterranean area by the expansion of herbaceous plants during the main lowering of both temperature and humidity (Bertini, 2010; Combourieu-Nebout et al., 2015; Suc & Popescu, 2005; Figure 9). On the contrary, the pollen assemblage is characterised by the disappearance of *Abies* and by a notable increase of the evergreen oak (*Q. ilex*), suggesting the beginning of a warmer period associated with an interglacial/

interstadial phase. The high percentages of Mediterranean taxa support a high seasonality during the dominantly hot, dry summers and cool, wet winters. According to this reconstruction, the acme of an arid/cold phase, as described within an ideal glacial/interglacial cycle, is lacking in this portion of the flowstone. The highest values of deciduous *Quercus* found in ONC 33L are growing evidence of strongly ameliorated environmental conditions possibly during a climate optimum. Close to the top of the flowstone a new expansion of mountain taxa (*Fagus* and *Picea*), along with a decrease in deciduous and evergreen oaks, attest to decreasing temperatures. The acme of this climate deterioration would not be fully recorded because flowstone growth was interrupted, possibly during the subsequent phase of reduced precipitation. So, the severe climate change associated with the major decrease in both temperature and humidity could be the cause of the interrupted carbonate deposition.

5.3 | Chronostratigraphic meaning of the flowstone growth phases: Preliminary inferences

Palaeoclimate and palaeoenvironmental changes inferred from flowstone depositional features and its pollen content can be tentatively placed in a stratigraphic context according to the available chronology (Figure 10). According to Piccini et al. (2003), the upper portion of the flowstone has an age exceeding the limits of alpha U/Th dating (>350 ka), whereas the basal core of a stalagmite growing on the flowstone dates to 290 ka. Assuming a typical grow-rate of 30 mm/ka (Baker & Smart, 1995, and references therein) an age of at least 450–500 ka can be inferred for the base of the flowstone. Furthermore, during the latest Early Pleistocene the hydrological base level of the Frigido River should be placed at a higher elevation than BOMG; therefore, the phreatic phase of this cave is reasonably referred to a later speleogenetic stage (Piccini, 1998; Piccini et al., 2003). This assumption is mainly based on the ages of speleothems sampled at Galleria delle Stalattiti in the Corchia cave system. The latter is about 300 m above the present elevation of BOMG and dates back to about 1 Ma (Piccini, 2011; Woodhead et al., 2006). No differential lowering of the local base levels can be presumed between the Frigido River and the Vezza Creek, where the Corchia cave is located, just a few kilometres to the south-east (see Figure 1).

According to the previous assumptions, it is believed that BOMG was still active as a phreatic conduit in the first part of the Middle Pleistocene, and that the flowstone probably grew mainly between 500 and 300 ka (i.e. between MIS 13 and MIS 10). This hypothesis is in quite good agreement with the palynological assemblage that does not contain older Pleistocene taxa. Finally, an age of about 500 ka is also

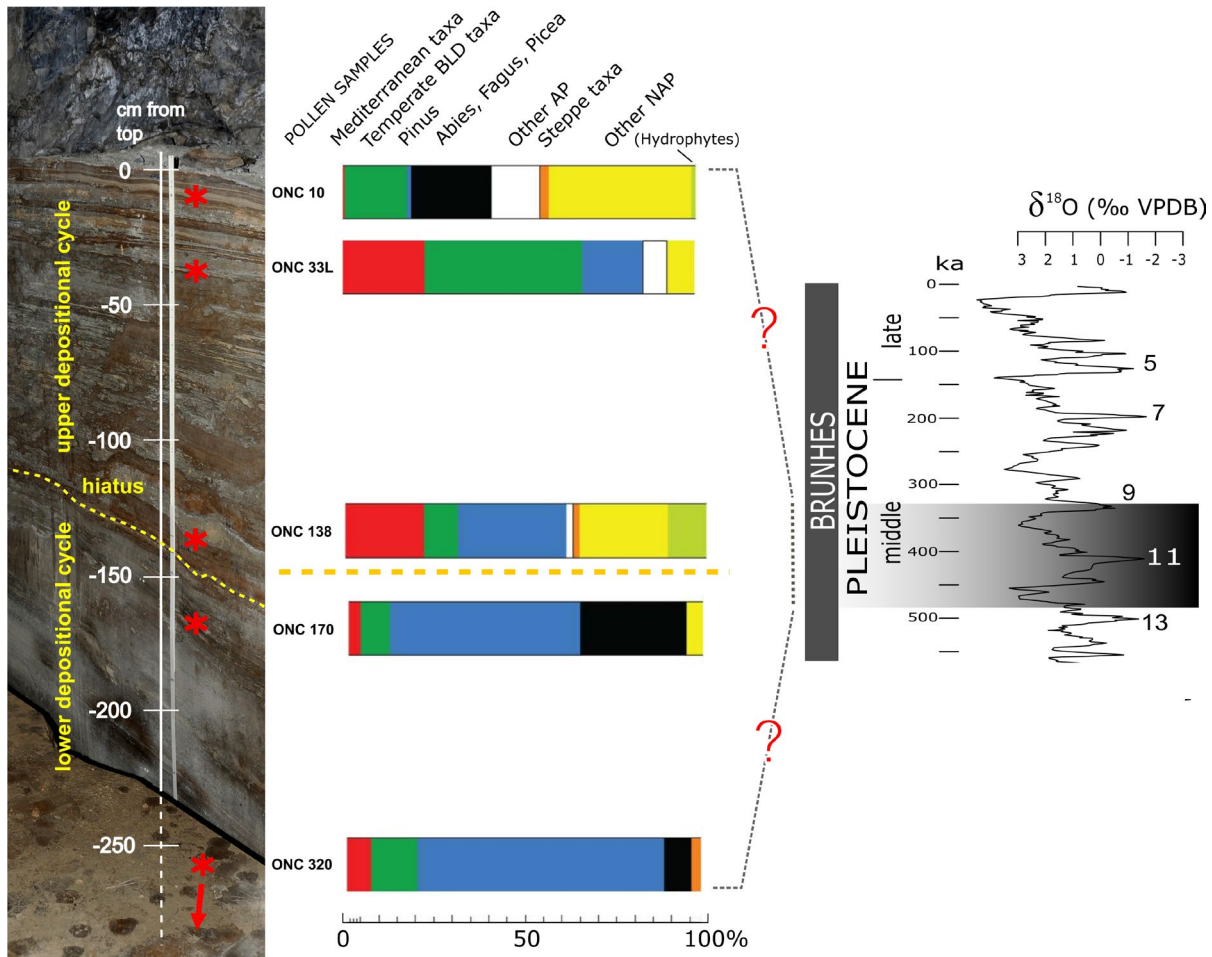


FIGURE 10 BOMG flowstone: summary pollen diagram and its stratigraphic framework. BLD = Broad-leaved deciduous taxa. The Mediterranean $\delta^{18}\text{O}$ planktonic foraminifer *Globigerinoides ruber* stacked record is from Lourens (2004, and references therein)

in good agreement with the estimated 0.6–0.8 mm/yr uplift rates determined for the Alpi Apuane during the Pleistocene by a number of different methods (Balestrieri et al., 2003; Fellin et al., 2007; Piccini, 2011). This rate of uplift would place the BOMG phreatic passages about 400 m above the present hydrogeological base level (Piccini et al., 2003).

The two taxa, *Picea* and *Carya* allow for some additional stratigraphic considerations. *Picea*, was largely present in the area surrounding the cave ca 500 ka, while it is no longer a natural part of the current landscape today despite a relict population in the Tuscan-Emilian Apennines (Sestaione valley near the Abetone Pass; Romagnoli & Foggi, 2005). The discovery of exceptionally preserved examples of *Carya* in the flowstone suggests that this plant grew in close proximity to the site. This genus, belonging to the family Juglandaceae, is today distributed in subtropical and temperate continental biomes (North America in the United States, Canada and Mexico, and South-East Asia in China, Vietnam, Laos and India) characterised by rainfall values between 1,000 and 1,500 mm/year (Fang et al., 2011; Manchester, 1989; Orain et al., 2013). This genus was rather common in Central Europe and the Mediterranean area during the Miocene

and Pliocene (Jiménez-Moreno et al., 2008, 2010; Kovar-Eder et al., 2006; Pontini & Bertini, 2000). In the eastern Mediterranean, sparse grains of *Carya* were recovered up to MIS 8 at Lake Ohrid (Sadori et al., 2016; Figure 1). In Italy, *Carya* exhibits a general increase in pollen percentage values towards the end of the Gelasian and during the Calabrian (up to MIS 31), whereas it is much less abundant later (Bertini, 2010 and references therein). At present, the last documented occurrence of *Carya* is at Boiano, a southern site (Figure 1), attributed to MIS 9 (Orain et al., 2015). In central Italy, the occurrence of *Carya* is quite sporadic in Middle Pleistocene deposits (Bertini, 2010; Magri & Palombo, 2013) but its recovery at BOMG suggests that the Alpi Apuane possibly acted as a refuge area.

Palynological data (Figures 8 and 10) document flowstone growth during the warm and humid conditions (interglacials/interstadials) when changes in the Meridional Overturning Circulation in the Atlantic were promoting vapour masses in this portion of the Mediterranean (Drysdale et al., 2009). However, persistent growth is also indicated during the initial phase of decreasing temperature, together with the high humidity often seen at the end of interglacials. At BOMG the

corresponding samples exhibit the higher pollen concentrations (see samples ONC 170 and ONC 10), probably related to an altimetric lowering of the montane plants bringing them closer to the site as the climate deteriorates.

Despite the lack of precise dates for the flowstone, it can be assumed that the major stratigraphic discontinuity at 1.43 m below the top surface, indicates a prolonged interval when growth was interrupted corresponding to the dry conditions typical of a glacial/stadial phase (Isola et al., 2019). According to both palynological (absence of steppe/open vegetation phase in the pollen record) and geo-stratigraphic evidence, the main interruption of the calcite flow could be related to the appearance of the driest conditions during the glacial/stadial maximums within MIS 12–MIS 10 (Figure 10), possibly during global colder conditions which reduced advection of water masses from the Atlantic. The textural discontinuities also indicate changes in the flowstone water supply and a more significant contribution from local drips, probably also accompanied by a significant change in external morphology.

6 | CONCLUSION

The Alpi Apuane is a key area for the study of the late Quaternary as previously demonstrated by the many geochemical/isotopic studies performed in this area, as well as by numerous dates obtained from terrestrial carbonates, mainly speleothems. The latter allow the main palaeoclimate events to be placed within a precise chronostratigraphic framework and establishes significant correlations with the other natural archives of palaeoclimate (marine/continental sedimentary successions, ice cores). While palynology does not guarantee both a high resolution and continuous record, in the right circumstances it could be considered an efficient and integrative survey tool.

This pilot investigation of the BOMG flowstone demonstrates its excellent potential for the study of the Alpi Apuane terrestrial carbonates as it can deliver some unique information on:

1. floral composition and vegetation cover;
2. the environments and climate prevalent during flowstone growth as well as the phases of interrupted growth.

This made it possible to picture the landscape based on floral and vegetational evidence at a local to regional scale as well as to detect and understand the regional response to global climate change.

In conclusion, BOMG promises to be an excellent site where Middle–Late Pleistocene climate and environmental changes are recorded by calcite precipitation, detrital deposition and pollen content, also providing the opportunity to compare and tune different analytical methods and palaeoenvironmental proxies. These preliminary results justify a future

in-depth multi-proxy study including geochemical investigations and new and more dates. The acquired experience will allow for improved methodology, especially in the sampling phase, in order to extract a very high number of samples, permitting more detailed analysis over reduced intervals.

ACKNOWLEDGEMENTS

This research was financially supported by Università degli Studi di Firenze (Fondi di Ateneo A. Bertini, L. Piccini and a Ph.D. fellowship to M. Ricci). Two anonymous reviewers are thanked for their insightful and critical reviews. Thanks are also due to Greta Mackenzie for English language editing.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Bertini A, Piccini L, Ricci M, Massini M. Palynological evidence of Middle Pleistocene palaeoenvironmental changes from the ‘Buca dell’Onice’ flowstone (Alpi Apuane, Central Italy). *Depositional Rec.* 2021;00:1–15. <https://doi.org/10.1002/dep2.140>