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RESEARCH

Late Mid-Pleistocene hominin fire control inferred from sooty speleothem analysis

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Abstract

The origin of fire control is considered a major turning point in human evolution and remains a highly debated albeit central subject in archaeology. Studying paleo-fires is challenging because of taphonomic phenomena that alter combustion structures and hinder the identification of the oldest hearths. Moreover, hearths do not record all fire events and do not provide a chronological record of fire. In contrast, speleothems, carbonated cave deposits, can preserve evidence of ancient fires, including soot traces, and these features can be dated directly using radiometric methods. Orgnac 3, an important archaeological sequence in Western Europe, provides a case study on the origins of habitual fire use in this region during the transition between the Lower and Middle Paleolithic. This paper presents the first documented record of over 20 fire events at this ancient site. The habitual use of fire by Mid-Pleistocene hominins at the site is well documented within sooty speleothems, as opposed to relying on scattered and rare traces. The soot deposit sequence at Orgnac 3 is the strongest and best-documented evidence of repeated fire use at the site to date. The robust fire-use chronology is established using stratigraphic U-Th dating of the speleothem. The soot record at Orgnac 3, testifying to fire events during both dry and wet periods, supports the hypothesis that Mid-Pleistocene hominins could control fire around 270,000 years ago in the Rhone Valley, with the possible ability to light it, or at least maintain it over a long term.

Keywords Mid-Pleistocene hominins · Fire control · Lower to Middle Paleolithic transition · Pyroarchaeology · U-Th dating

Significance Statement
- The Orgnac 3 site provides an ideal case study to study the emergence of fire control in Europe by ancestors of *H. neanderthalensis*, whose ability to control fire from its ignition remains debated.
- Relying on multiple approaches, our investigation of a sooty speleothem significantly contributes to our knowledge about the origins of fire control in western Europe.
- We provide evidence of anthropogenic use of fire that includes fire control, and probably ignition capabilities, by Mid-Pleistocene hominins ca. 270,000 years ago.

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Introduction

The use of fire is considered a crucial turning point in human evolution, playing a central role in hominin development (Gamble *et al.*, 2011; Karkanas, 2021; Lumley de, 2006; Shimelmitz *et al.*, 2014; Walker *et al.*, 2016). Fire serves multiple functions, such as providing heat, light, and means for cooking. It also acts as a tool, allowing early "engineering"; it is an early "transformative" technology regarding alteration of raw materials (*i.e.*, stone tool heat treatment, adhesive manufacture) (Brown *et al.*, 2009; Schmidt *et al.*, 2020). Fire also acts as a social gathering place (Bentsen, 2020; Perlès, 1977; Twomey, 2014). However, fire brings its own set of challenges, including its maintenance and surveillance, as well as fuel collection and fire management, requiring a reorganization of tasks within a group. Fire contributes to the hominization process in various ways, influencing group organization and expanding possibilities for control over materials and new experiences that facilitate psychic development (Perlès, 1977). Therefore, the timing of fire control by our ancestors remains a major topic of debate among archaeologists. For a long time, fire control was believed to be a necessary prerequisite for the settlement of areas outside of Africa, particularly in the higher latitudes of Europe, which experiences colder temperatures, especially during winter. However, despite the first evidence of fire use appearing in Africa around 1,600,000 years ago, the habitual use of fire in Europe only emerged between 400,000 and 300,000 years ago, approximately 700,000 years after European settlement (Roebroeks & Villa, 2011).

Although traces of ancient fire can be found, their accurate identification becomes even more challenging as the age of the traces increases (Roebroeks & Villa, 2011; Gowlett *et al.*, 1981; Barbetti, 1986; Goudsblom, 1986; James *et al.*, 1989; Bellomo, 1993; Pickering *et al.*, 2008; Gowlett & Wrangham, 2013; Goldberg *et al.*, 2017; Lebreton *et al.*, 2019; Roebroeks *et al.*, 2021). Whereas most analyses focus on visible remains, recent advancements (*e.g.*, archaeomagnetic and spectroscopic analyses) permit detecting invisible fire residues (Stepka *et al.*, 2022; Zohar *et al.*, 2022). These techniques can help determine whether heating occurred on bones or lithic artifacts at ancient sites where visible traces of fire tend to disappear.

Another challenge is distinguishing between fire used by humans and fire caused by natural phenomena such as volcanic eruptions and lightning strikes that lead to burning at archaeological sites (Dibble *et al.*, 2018; Sorensen, 2017). The presence of fire-affected elements alone is therefore insufficient evidence to conclude that hominins used fire. Additionally, early hearths were not well structured and typically consisted of simple lenses or depressions, comprising burnt material associated with fragmented charcoals on a reddened ground (Roebroeks & Villa, 2011). Identifying these fire-affected materials through macroscopic observations alone is often difficult (Aldeias *et al.*, 2012) given the various post-depositional and taphonomic processes that affect hearths (March *et al.*, 2014; Scott & Hosfield, 2021; Théry-Parisot, 2001), including the weathering of charcoal (Chrzavzez, 2013; Chrzavzez *et al.*, 2014), organic residue (Théry-Parisot *et al.*, 2010), and ash (Karkanas, 2021; Shahack-Gross & Ayalon, 2013; Shahack-Gross *et al.*, 2008; Toffolo *et al.*, 2023), and the alteration of the structures themselves (Mallol & Henry, 2017; Mallol *et al.*, 2007). The poor preservation of ancient fireplaces makes it challenging to conclusively demonstrate the repeated use of fire by hominins during early periods (Roebroeks & Villa, 2011). Consequently, evidence of anthropogenic fire use remains sporadic even in the early Middle Paleolithic period (Karkanas *et al*., 2007; Roebroeks *et al*., 2021). To address these difficulties and avoid unfounded claims about early fire control, Stahlschmidt *et al*. (2015) advocated a multi-analytical and contextualized approach.

If ancient fires are difficult to identify, documenting the recurrence of fire episodes for ancient periods is even more challenging. The dispersal of hearths in space can complicate this identification, as they may or may not have been used simultaneously (Herrejón-Lagunilla *et al*., 2024). The re-use of a fireplace can sometimes be demonstrated through micromorphological analysis, which can identify multiple superposed combustion events that cannot be distinguished during field excavation (Aldeias *et al*., 2012), but only if the structure is well preserved. Identifying this re-use is a critical challenge because the "control of fire" and its "habitual use" are crucial milestones in the history of human development (MacDonald *et al*., 2021).

Before proceeding, it is important to clarify the terminology currently used in the literature in regard to the different uses of fire with varying degrees of control (Sandgathe, 2017). For example, terms such as "opportunistic" or "fortuitous" versus "controlled" use of fire are encountered (Bentsen, 2014; Goren-Inbar *et al*., 2004; James *et al*., 1989; Sandgathe, 2017; Shimelmitz *et al*., 2014). Even the term "controlled" fire does not have a consistent meaning among authors (Sandgathe, 2017). In the case of the Orgnac 3 site central to our study, we will not use the term "controlled" to refer to basic fire use. The occupation of the site does not date to the Lower Pleistocene, and we know that fire had been used in the Middle Pleistocene even if traces in Europe are scarce (Roebroeks & Villa, 2011). Fire traces have been documented at Cueva Negra del Estrecho del Río Quípar (Spain), dating to ca. 800,000 years ago (Lebreton *et al*., 2019; Walker *et al*., 2016), and cooking with fire has been identified at around 780,000 years ago in the Levant (Goren-Inbar *et al*., 2004; Zohar *et al*., 2022).

The question for the Mid-Pleistocene context at Orgnac 3 is more about the controlled use of fire in terms of its maintenance and/or manufacture. Controlled use does not necessarily mean the ability to create fire at will; it can also refer to a reliance on natural fire sources although with the ability to maintain this naturally sourced fire. In this paper, we add precision (*e.g*., "control, including ignition") to avoid ambiguity when discussing the ability to make fire. Similarly, the notion of "habitual fire" use is relative and depends on the temporal resolution of archaeological data. Although this term has gained popularity in recent years (Barkai *et al*., 2017; Goldberg *et al*., 2017; Karkanas *et al*., 2007; MacDonald *et al*., 2021; Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe *et al*., 2011b; Shahack-Gross *et al*., 2014; Shimelmitz *et al*., 2014), it generally refers to the repeated use of fire at a specific site or in a given region over a period that can span several thousand years. We will discuss this notion in light of the new data presented in this paper.

The discovery and recent study of a sooty speleothem (carbonates interspersed with soot-rich layers) at the Orgnac 3 site (Orgnac-L'Aven, France) brings new elements and makes it possible to address these fundamental archaeological issues about identifying anthropogenic fire as well as the origin of its controlled use. According to the latest U-Th and $^{40}Ar/^{39}Ar$ data from Orgnac 3, the infilling of the site would have occurred between ca. 330,000 and 260,000 years ago (Michel *et al.*, 2013). A recent chronological study by Bahain *et al.* (2022) and the TL and ESR/U-series data they provide confirm the attribution of the archaeological sequence to MIS 10–MIS 8, in agreement with a previous chronology based on U-series dates on speleothems. A recent publication based on faunal and geologic data extends the chronology from MIS 12 to MIS 8 (Lewis *et al.*, 2022). In terms of technological evolution, Orgnac 3 records the transition from the Lower to the Middle Paleolithic through a progressive emergence of the Levallois concept among flaking technologies (Combier, 1967; Mathias *et al.*, 2020; Moncel *et al.*, 2005, 2020). It is one of the largest, richest, oldest, and most important Middle Pleistocene sites in Europe, containing one of the longest and oldest archaeological and paleontological sequences. Moreover, in Western Europe, only the Gruta da Aroeira (Portugal) and Vértesszőlős (Hungary) for the same period (MIS11–MIS9), and Biache-Saint-Vaast (France), Lazaret Cave (France), and Bolomor (Spain) for more recent periods (MIS7–MIS5e), contain simultaneously lithic, faunal, and hominin remains, as well as good evidence of fire (Roebroeks & Villa, 2011) (Fig. 1). During the early Middle Paleolithic, traces of fire prior to MIS 9 in Europe are rare, and the amount of evidence of fire increases during MIS 7 and MIS 6 (see Supplementary Note 1: Table S1).

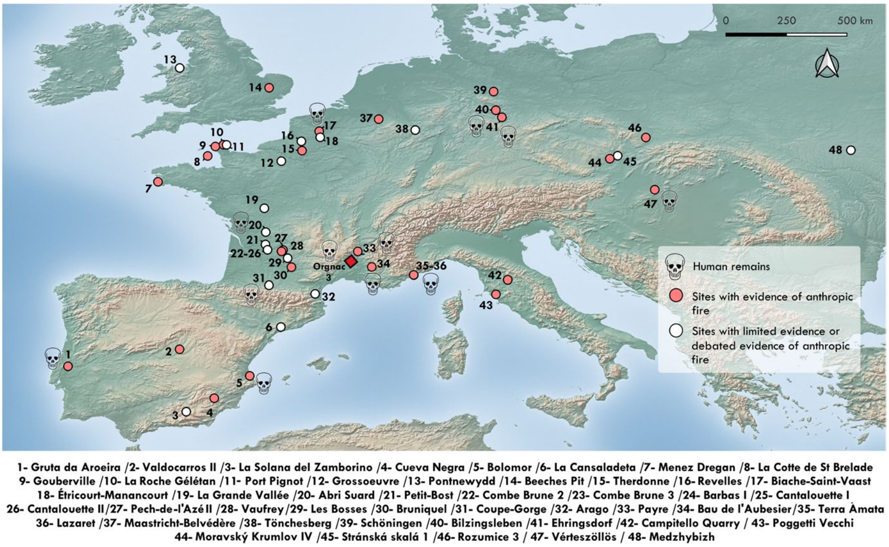

Fig. 1 Early traces of fire in archaeological sites in Western Europe. Relevant information related to these sites (including chronological information) is summarized in Table S1 (Supplementary Note 1 online). The map was created using QGIS 3.16.16, and raster data were obtained from Natural Earth (https://www.naturalearthdata.com/)

The Orgnac 3 site is therefore an ideal site to study the emergence of the habitual use of fire in Europe, by the ancestors of *H. neanderthalensis*, whose ability to control fire (including fire ignition) remains debated (Sandgathe *et al*., 2011a, 2011b; Sorensen, 2017; Sandgathe, 2017; Dibble *et al*., 2018; Sorensen & Scherjon, 2018; Sorensen, 2019). The analysis of a sooty speleothem at the site permits reconstructing a paleo-fire chronology and a direct dating of these events. We discuss the (natural or anthropogenic) nature of the fires that left these soot traces and address how these traces shed light on the harvesting and ignition capacities of late Middle Pleistocene hominin populations (either late *Homo heidelbergensis* or early *H. neanderthalensis*—see Supplementary Note 2) at Orgnac 3.

Materials

During their excavations, J. Combier and his team discovered and sampled a speleothem, Org3-fsp1, found on a limestone block and named "Australia" because of its unique shape (Fig. 2). One of us (L. Slimak) identified black deposits, likely caused by soot, in this speleothem. The "Australia" block is located halfway up the stratigraphy in the third main geological context (Complex III) as defined by Debard (1988) and Khatib (1989, 1994). Originally, the Australia boulder was situated on the vault of the cave near the entrance. The Org-fsp1 speleothem could have formed either on the boulder when it was part of the vault or after it fell. The speleothem's base is positioned at the top of archaeological level 4b, whereas the remaining portion is found at the base of archaeological level 4a subdivisions as defined by Combier (1967) and Debard (1988). Consequently, the formation of Org3-fsp1 is contemporaneous with or predates archaeological level 4 (C.III, AL4). Older archaeological levels 6 and 5 correspond to a generally temperate and humid phase, whereas archaeological level 4 reflects a generally cold and humid phase (Michel *et al*., 2011). Archaeological level 4 documents a combination of "old" and "new" technical approaches with both the manufacture of bifaces (although fewer than in archaeological level 5) and an increasing use of Levallois debitage (Combier, 1967; Moncel *et al*., 2012).

The forming of the Org-fsp1 speleothem depended not only on physicochemical processes. The presence of its microcrystalline fabric and budding structure (resembling stromatolite-like tufa; see Fig. 3, and Figures S1, S5, S6, and S7 in Supplementary Notes 3 and 4) indicates the involvement of microorganisms and the occurrence of biological action (Chiarini *et al*., 2017; Frisia, 2015; Frisia & Borsato, 2010), as evidenced by porosity and irregular voids. Non-isopachous laminations are attributed to phototrophic organisms (Chiarini *et al*., 2017). UV spectrofluorescence observations of the Org-fsp1 speleothem reveal a shoulder in the fluorescence spectrum (Supplementary Note 9), indicating the presence of aromatic amino compounds. This supports Frisia's (2015) suggestion that these stromatolite-like structures are associated with organic compounds and likely microbial laminae. Hence, Org-fsp1 is not a conventional speleothem formed in complete darkness; rather, its structure suggests formation in an environment exposed to natural light. This proximity to sunlight is consistent with the cave entrance and the site's opening, resulting

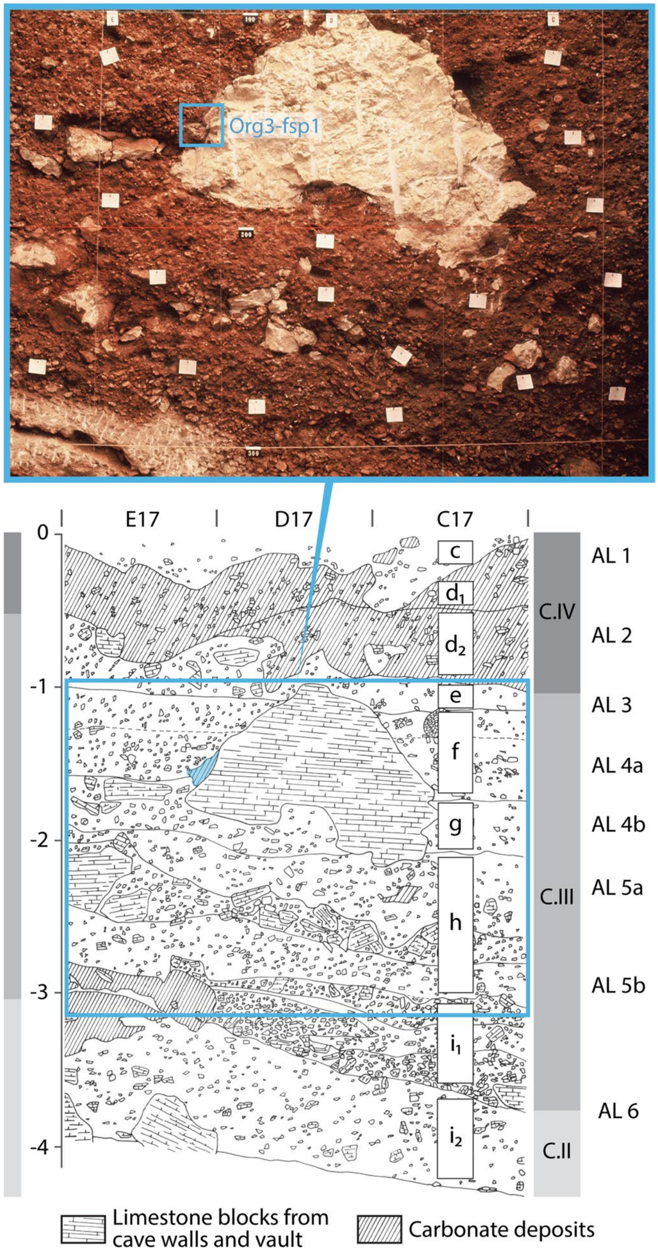

Fig. 2 Location of the fuliginous speleothem Org3-fsp1 (blue box) in the upper part of the Orgnac 3 stratigraphy. Photograph by Erwin Tscherter (modified) and drawing "stratigraphie des couches supérieures" from Debard (1988) (modified and completed with data from Michel *et al*., 2011) showing the Org3-fsp1 carbonate deposit (in blue) on the "Australia" limestone boulder. Abbreviations: C. = complex (II, III, IV); AL = archaeological level; c to i_2 = denomination of stratigraphic levels (established by Combier, 1967 with subdivisions from the sedimentological study of Debard, 1988). Excavation squares are labeled on the horizontal axis, and the vertical axis indicates the depth in meters

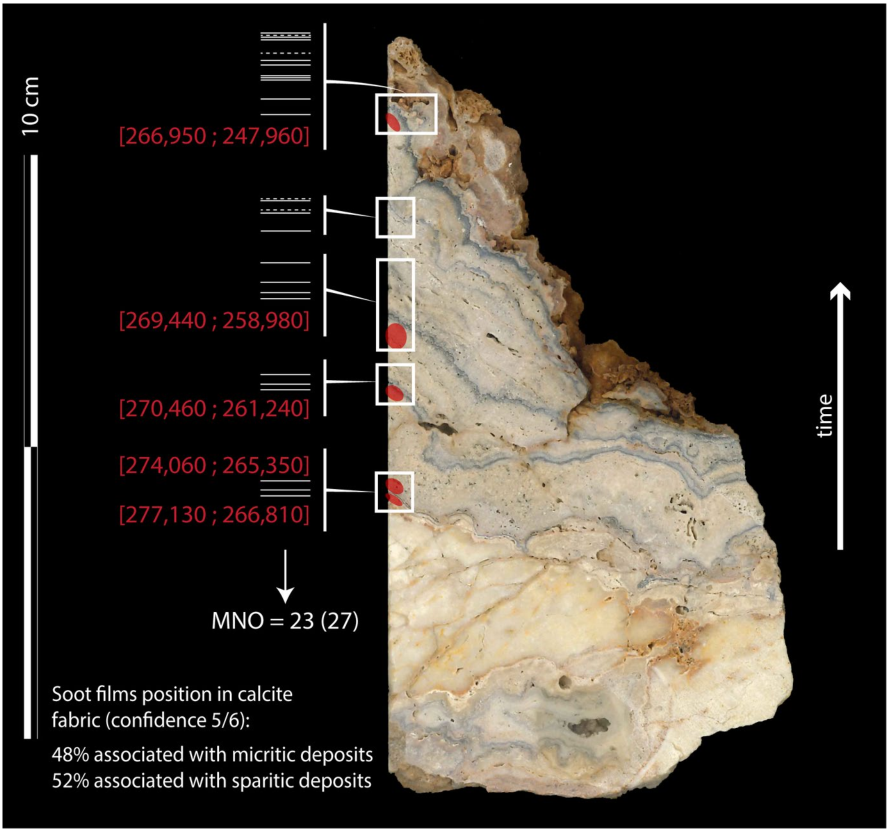

Fig. 3 Synthesis of results obtained through fuliginochronological study and stratigraphic dating of Org-fsp1 sample. The locations of the U-Th dating (performed on Org-fsp1-s2) are indicated by the red shaded areas, and the U-Th dates (minimum and maximum ages in years, respectively) are presented in red. The barcodes (left of the sample) represent the succession of soot films observed in the Org-fsp1 sample. The five separated areas of soot accumulation are indicated by the white squares and extended at different scales to show all the soot films. See Figure S7 to see the succession of soot films without various scales extensions. Each solid white line represents a counted soot film; dotted lines represent possible soot films. Their counting shows an MNO or minimum number of 23 occupation events (27 if probable soot films are also counted); 48% of the occupation events are associated with micritic deposits, which form during dry periods, and 52% are associated with sparitic deposits, which form during wet periods

from the gradual collapse of the cave ceiling during Complex III, as evidenced by the "Australia" boulder's fall.

This carbonated formation is laminated, and three types of crystalline fabrics can be identified (Supplementary Note 4): sparite (> 10-µm calcite crystals), microsparite (5- to −10-µm calcite crystals), and micrite (< 5-µm calcite crystals). Sparite and microsparite form during periods of excessive moisture, whereas micrite forms in drier conditions (Fairchild *et al.*, 2000; Foucault *et al.*, 2014; Genty & Quinif, 1996). The lamination of speleothems is mainly influenced by variations in hydrological conditions (Baker *et al.*, 2008; Fairchild *et al.*, 2000; Frisia & Borsato, 2010;

Frisia *et al.*, 2000; Genty, 1992, 1993), which can be marked by seasons. A pair of micritic and sparitic laminae, known as a calcite doublet, may correspond to an annual cycle (Allison, 1926; Genty, 1993); however, this pattern does not always represent an annual deposit (Baker *et al.*, 2008; Shen *et al.*, 2013) and must be demonstrated on a case-by-case basis (Vandevelde *et al.*, 2021). In the Org-fsp1 speleothem, sparite is present in fractures and appears to be linked not to the initial speleothem formation process but rather to subsequent crystallization processes in cracks. Micrite, on the other hand, is generally a primary fabric favored by bio-mediated processes during periods of reduced water flow when associated with stromatolite-like structures. However, in aragonitic speleothems, micrite can sometimes have a diagenetic origin (Frisia, 2015; Frisia *et al.*, 2012). Microsparite alternates here with micrite, and its formation can also be linked to the presence of microorganisms that can facilitate its growth (Frisia, 2015). In microsparitic layers, microsparite is also associated with micrite, which testifies to the *in situ* maturation of micrite when the formation conditions change because of the reactivation of water runoff flow (Frisia, 2015). Therefore, changes in biological activity and variations in water flow play a role in the alternation of these micritic and microsparitic layers in the Org3-spf1 speleothem. This pattern is not necessarily indicative of seasonal variations. The alternating crystalline fabric, clearly visible on both sides of the thin section, differs from the sparmicritization (post-depositional alteration) observed in the center of the sample, which has partially erased the laminations that are still visible on the sides of the speleothem.

To determine whether the changes in crystalline fabric are seasonal, we analyze minor and trace elements showing annual fluctuations in calcium carbonates (*e.g.*, Mg, Sr, Ba, and U) to determine whether they synchronize with changes in fabric (Hellstrom, 1998; Roberts *et al.*, 1998; Desmarchelier, 1999; Hellstrom & McCulloch, 2000; Fairchild *et al.*, 2000, 2001, 2006; Finch *et al.*, 2001; Huang *et al.*, 2001; Huang & Fairchild, 2001; Treble *et al.*, 2003; Borsato *et al.*, 2007; Bourdin *et al.*, 2011; Bourdin, 2012; Nagra *et al.*, 2016, 2017; Faraji *et al.*, 2021; Vandevelde *et al.*, 2021). This method has been successful in caves and speleothems formed by physicochemical processes (*e.g.*, Nagra *et al.*, 2017; Faraji *et al.*, 2021). A recent study of parietal crusts in a rock shelter showed that the patterns for incorporating minor and trace elements in this type of open environment were similar to those of caves: Annual elemental Sr variations documented through µLIBS were synchronized with calcite laminations in an open context in which microbial activity led to the formation of corraloid-like carbonated crusts (Vandevelde *et al.*, 2021). Furthermore, in a more open environment, the partial pressure of CO_2 in the cave—which influences the growth rate of carbonates (Genty *et al.*, 2001a, 2001b) and therefore Sr incorporation into calcium carbonates (Fairchild *et al.*, 2000, 2006; Huang & Fairchild, 2001; Lorens, 1981; Tesoriero & Pankow, 1996; Treble *et al.*, 2003)—is also closer to the atmospheric partial pressure of CO_2, whose annual variation amplitude is greater than that in caves, amplifying the recording of the seasonal signal (Vandevelde *et al.*, 2021 and references therein). In the case of a cave entrance speleothem like Org3-fsp1, whose context is intermediate between the classic speleothems formed inside caves and the budding wall carbonated crusts formed in rock shelters, this approach is therefore also adequate. As the speleothem here is of a multi-centimeter (and not submillimeter) scale, we did not use μLIBS mapping to document variations in minor and trace elements, such as Vandevelde *et al.* (2021), but rather ran LA-ICP-MS transects, as performed by Desmarchelier *et al.* (2006) and Nagra *et al.* (2017) (cf. the "Methods" section and Supplementary Note 7 online for the experimental parameters).

Many dark laminae can be observed in the Org-fsp1 speleothem. The black laminae in speleothems have several origins, such as Mn-Fe oxides (*e.g.*, Jones & Northup, 2021), bacteria, guano (*e.g.*, Kaal *et al.*, 2021), and char residues (Brochier, 2008; Deldicque *et al.*, 2023; Genty *et al.*, 1997; Martínez-Pillado *et al.*, 2014; Vandevelde *et al.*, 2020). Using a scanning electron microscope (SEM), energy-dispersive X-ray spectroscopy (EDX), and micro-Raman spectroscopy (Supplementary Note 3 online), we characterized these deposits and revealed that they consisted of soot trapped in the carbonated matrix. Soot can adhere to speleothems through thermophoresis, as documented by experimental observations (Vandevelde *et al.*, 2023), or through sedimentation, as observed in stalagmites in Han-sur-Lesse, Belgium (Genty *et al.*, 1997; Verheyden *et al.*, 2006), and the Nerja cave, Spain (Medina-Alcaide *et al.*, 2023; Pons-Branchu *et al.*, 2022), which both recorded soot falling from torches. Thermophoresis is a microscopic force driven by a temperature gradient and aerosol concentrations, which causes aerosols to move from hot to cold zones (Bellivier, 2017; Decoster, 2017). Sedimentation occurs when cooled aerosols fall because of their own weight (Bellivier, 2017; Decoster, 2017). In the case of the Org3-fsp1 speleothem, the soot may have adhered through thermophoresis if the "Australia" boulder was still part of the vault or through sedimentation if the speleothem formed on the ground after the boulder fell. Regardless, this sooty speleothem, dated using U-Th (cf. the "Methods" section and Supplementary Note 5 online), serves as an archive that records and preserves numerous paleo-fire events.

Methods

Building the Paleo-fire Chronology

To reconstruct the chronology of paleo-fires in the sooty speleothem, we identified, individualized, and documented each soot film in chronological order of formation using a fuliginochronological approach (Vandevelde, 2024). We cut and prepared the speleothem into five polished sections to observe the succession of soot films (Supplementary Note 3; Fig. S1 online). However, because of the budding structure of the carbonated deposit, some soot films had an anastomosed pattern, making individualization challenging. Following a soot film completely and avoiding counting the film multiple times can be difficult. Therefore, we built the chronology from a section (Org3-fsp1-s1) that we cut in the growth axis of the speleothem, perpendicular to the laminae. To ensure the accurate identification of soot films, we also studied and compared all the different sections.

Documenting the Position of Soot Films in Relation to the Crystalline Fabric

To observe the thick black laminae more closely, we prepared a thin section of Org3-fsp1-s1 for microscopic observation. The microscopy analysis was conducted using the equipment of the MAPS Platform of MSH Mondes (USR 3225 CNRS, Nanterre, France). We used a Nikon Eclipse E600 POL polarizing microscope to perform the microscopic observations. By combining incident and transmission light, including an incident fiber-optic light source (Leica Schott KL 1500 LCD Illuminator), as in references (Vandevelde *et al.*, 2017, 2018, 2020, 2021), we were able to study both the variations of the crystalline fabric and the soot films (Supplementary Note 4 online). This analytical parameter was chosen to document the position of the soot films in relation to the micritic and sparitic calcite layers.

We did not use the microstratigraphic log system developed by Frisia (2015), as it was intended for more "classic" speleothems such as stalagmites and flowstones. Moreover, in this speleothem, we only have two values, with a micrite/microsparite alternation (primary form, as described in the "Micritic Fabric" section by Frisia, 2015). The position of the soot films in relation to these deposits has been codified in a table (see Supplementary Note 6, Tables S2 and S3 online).

U-Th Dating of the Sequence

Another section, Org3-fsp1-s2, was cut parallel to Org3-fsp1-s1 along the growth axis of the speleothem. The soot films present serve as reference horizons, allowing us to easily match it with Org3-fsp1-s1 (Supplementary Note 5; Fig. S8 online) and produce a precise paleo-fire chronology. We sampled between 50 and 160 mg of material along the growth axis using a micro diamond saw. Sampling avoided soot deposits and areas with cracks or corrosion in order to date the cleanest calcite as possible. Petrographic analysis performed on Org-fsp-s1 did not show any traces of dissolution and recrystallization anywhere near the sampling locations.

The five stratigraphic samples were dissolved in diluted hydrochloric acid in beakers containing a known amount of ^{229}Th-^{233}U-^{236}U tracers calibrated against HU-1 uraninite, which is assumed to be at secular equilibrium and was previously weighed. After iron coprecipitation, the uranium and thorium fractions were separated and purified using U-TEVA resin and a series of nitric and hydrochloric acid washes. The analyses were performed at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif sur Yvette, France) using a Thermo Scientific Neptune^{Plus} multi-collector inductively coupled plasma-mass spectrometer equipped with a jet pump interface and an Aridus II desolvating system. The detailed procedure is outlined by Pons-Branchu *et al.* (2014).

The ^{230}Th/U ages, expressed in years before the year 2000 (B2k), were calculated based on measured isotopic ratios using iterative age estimation and the ^{230}Th, ^{234}U, and ^{238}U decay constants of Cheng *et al.* (2013) and Jaffey *et al.* (1971). A correction was applied to account for the non-radiogenic (detrital) ^{230}Th fraction, based on stratigraphic constraints, running the STRUTages routine (Roy-Barman & Pons-Branchu, 2016).

Documenting Trace Elements

A thin section of Org3-fsp1-s1 was used to analyze cyclical geochemical signals in the speleothem using LA-ICP-MS. The instruments, analytical conditions, and data reduction scheme are described in more detail in Supplementary Note 7. We focused on elements that are known to fluctuate on an annual basis, are relevant to speleothem formation, and contribute to paleoclimate reconstructions, *e.g.*, Mg, Sr, Ba, and U (as used in studies by Nagra *et al.*, 2017 and Desmarchelier *et al.*, 2006). We collected data along four transects that were aligned parallel to the central growth axis of the sample and that allowed us to determine the magnitude of variations. The first transect sets the acquisition parameters. Transects 2 and 3 covered the same part of the speleothem and showed consistent results. Transect 4 covered the end of the speleothem sequence, which required separate documentation to avoid areas of high porosity (budding due to bio-mediated processes and requiring reorientation of data collection) and to maintain alignment with the growth axis. The end of Transect 3 overlapped with the beginning of Transect 4 to ensure continuous data. The parameters were chosen to detect the elements of interest at concentrations above background, while optimizing spatial resolution using the necessary aperture for sub-seasonal resolution. These analyses were performed at the Centre d'Études sur les Ressources Minérales (CERM/LabMaTer, UQAC, University of Quebec at Chicoutimi, QC, Canada).

Counting Annual Cycles

Annual lamina counting is an established method in tree rings, ice cores, corals, lake sediments, and speleothems to reconstruct annually resolved records (Baker *et al.*, 1993). Using trace element data acquired through LA-ICP-MS, we constructed annually resolved chronologies by converting depth into time. To reduce noise, the data were smoothed using a moving mean over a $-5/+5$ window. The "find_peaks" function from the "scipy.signal" signal-processing library in Python was used to identify significant concentrations of chemical elements in each scan using a first derivative algorithm. The total number of positive peaks in scans 3 and 4 was then counted to determine the annual cycles while accounting for the overlap area. To estimate the number of annual cycles recorded in the Org3-fsp1 speleothem, we averaged the data for the four elements. It is important to note that U data may be slightly overestimated because of the low U concentrations, whereas data for other elements may be underestimated if only one element is considered at a time. Therefore, the uncertainty in this type of speleothem data is likely greater than the 2–4% achieved by Nagra *et al.* (2017) in their study; nonetheless, this approach still provides a more accurate view of the speleothem's growth time than direct radiometric dating alone.

UV Fluorescence Measurement and Lamina Counting

Fluorescence spectra were obtained using an experimental device for stationary fluorescence at EDYTEM Laboratory (Université Savoie Mont Blanc, CNRS, UMR5204, Le Bourget-du-Lac, France). The spectra were excited by a nanosecond-pulsed YAG laser beam at 266 and 355 nm with an energy of 1 lJ. The sample (another section, Org3-fsp1-s4, cut parallel to Org3-fsp1-s1 along the speleothem's growth axis) was placed on a two-axis translation stage to obtain fluorescence scans every 5 µm, repeated six times with a 100-µm lateral shift. A confocal optical setup directed the 15-µm laser beam orthogonally to the sample surface. Fluorescence scattering was analyzed using a monochromator (Jobin, Yvon Micro HR) and detected with a back-illuminated CCD (Syncerity S10420). The obtained spectra were then simulated by a MATLAB script using a linear combination of lognormal curves to distinguish the various known organic or mineral fluorescence.

UV fluorescence laminae counting was conducted using MATLAB toolboxes by applying a multiscale Daubechies wavelet filter to the signal within the range of 20 to 750 µm. The laminae were counted for each of the six scans.

Results

Microscopic observation of the Org3-fsp1 speleothem section in the growth axis allowed us to document 23 soot films, possibly 27 when considering uncertain soot films. These soot films were dated between ca. 277,000 and 248,000 years ago (see Table 1 and Fig. 3). These ages align with radiometric dating studies of the site (Bahain *et al.*, 2022; Michel *et al.*, 2013).

Elemental analysis using LA-ICP-MS revealed the preserved chemical signals in the speleothem. Chemical lamination was observed for Mg, Sr, Ba, and U, which experience annual fluctuations (*e.g.*, Desmarchelier, 1999; Desmarchelier *et al.*, 2006; Nagra *et al.*, 2017). These elements shared a similar number of peaks, suggesting that micrite–microsparite alternation was the primary fabric and not a result of diagenetic alteration, which could lead to a loss of this cyclical geochemical signal (especially U loss, as it is highly soluble; Lachniet *et al.*, 2012; Pons-Branchu *et al.*, 2022; Scholz *et al.*, 2014).

However, the micritic–sparitic alternation does not synchronize with cyclic variations of minor and trace elements, which fluctuate more rapidly than the changes in crystalline fabric. This indicates that two signals provided complementary information: an annual cycle accessed through trace elements and an environmental signal (alternating wetter and drier phases) characterized by crystalline fabric changes: during dry periods, micrite forms because of the very high supersaturation of the water or the formation of a microbial coating, whereas microsparite forms during wetter periods with reactivation of the flow (Frisia, 2015).

The geochemical signal of the speleothem revealed approximately 1020 cycles recorded in Org3-fsp1 (an average value based on the number of peaks recorded for Mg, Sr, Ba, and U— Supplementary Notes 7 and 8 online). This information

Table 1 Results of the U-Th dating. ^{238}U and ^{232}Th concentrations, isotopic ratios and ages. $\delta^{234}U = \{[(^{234}U/^{238}U)_{sample}/(^{234}U/^{238}U)_{eq}] - 1\} \times 1000$, where $(^{234}U/^{238}U)_{sample}$ is the measured atomic ratio and $(^{234}U/^{238}U)_{eq}$ is the atomic ratio at secular equilibrium. $\delta^{234}U_{(ini)}$ is the initial value and is calculated by the equation: $\delta^{234}U_{(ini)} = \delta^{234}Um\ \exp(\lambda^{234}t)$, where t is the corrected age in years and λ^{234} is the decay constant for ^{234}U. Ages are expressed as ky before measurement, *i.e.*, year 2016, and corrected ages are expressed as B2k (*k* years before the year 2000). The initial $^{230}Th/^{232}Th$ of the detrital fraction determined using STRUTages routine is 1.79 ± 0.25

Sample	$[^{238}U]$ ppm	$[^{232}Th]$ ppb	$\delta^{234}U$ (‰)	$(^{230}Th/^{238}U)$	$(^{230}Th/^{232}Th)$	Raw age	Corrected age	$\delta^{234}U_{ini}$ (‰)
Org-3_1.3–1.4	0.288 ± 0.002	57.56 ± 0.47	17.5 ± 1.4	0.951 ± 0.004	14.53 ± 0.06	290.22 ± 8.68	258.80 + 8.15 − 10.84	36.3 ± 3.1
Org-3_5-5.1	0.207 ± 0.002	27.65 ± 0.22	20.2 ± 1.1	0.953 ± 0.003	21.77 ± 0.06	287.50 ± 5.83	264.63 + 4.81 − 5.65	42.7 ± 2.3
Org-3_5.5–5.9	0.177 ± 0.001	20.63 ± 0.17	21.2 ± 1.2	0.944 ± 0.003	24.72 ± 0.08	274.56 ± 5.61	266.16 + 4.30 − 4.92	44.9 ± 2.6
Org-3_6.5–6.8	0.143 ± 0.001	8.89 ± 0.07	18.3 ± 1.2	0.944 ± 0.003	46.51 ± 0.14	279.02 ± 5.79	269.82 + 4.24 − 4.47	39.2 ± 2.7
Org-3_7.5	0.178 ± 0.001	49.50 ± 0.40	25.4 ± 1.8	0.962 ± 0.004	10.59 ± 0.04	291.95 ± 8.73	271.95 + 5.18 − 5.14	54.7 ± 3.9

provided insight into the chronology of the concretion's development. Moreover, the position of the films in relation to the alternating micritic and microsparitic deposits enabled discussion on the anthropogenic or non-anthropogenic nature of the fires recorded by the speleothem. Specifically, 48% of the soot films were associated with micritic laminae, whereas 52% were associated with sparitic deposits (confidence score = 5/6—Supplementary Note 6 online); thus, fire events occurred as often during wet periods as during dry periods.

We have unequivocally demonstrated the recurrence of more than 20 fires at a single site through the analysis of a speleothem that recorded the combustion products in the form of soot microlayers. This is the first instance of such findings at such an ancient site. We determined the age of the soot films using direct radiometric dating of the fuliginous speleothem. The age at the base is 271,950 years (+ 5180 / − 5140) and at the top is 258,800 years (+ 8150 / − 10,840), the recorded timespan ranges from 140 years (if we consider the narrowest dates, *i.e.*, 266,810 years at the base and 266,950 years at the top) to 29,170 years (if we consider the widest dates, *i.e.*, 277,130 years at the base and 247,960 years at the top). By estimating the number of annual geochemical cycles using the LA-ICP-MS data, we can establish that the speleothem was formed more precisely over a period of approximately 1020 years. This geochemical-based estimate aligns with the fluorescence laminae counting (914 doublets ± 10). Therefore, the Org3-fsp1 speleothem recorded the recurrence of 23 to 27 fires within a period of around 1000 years, approximately 270,000 years ago.

Discussion

Natural or Anthropogenic Fire Events?

The question of whether burnt residues and chars found on ancient sites are anthropogenic or natural must be answered. It can be challenging to confidently determine whether fire remains are indeed anthropogenic or the result of natural fires. In cave contexts with archaeological remains, the most parsimonious hypothesis is that fire traces are indeed anthropogenic (Berna *et al.*, 2012; Roebroeks & Villa, 2011; Sandgathe, 2017). However, in the case of speleothem Org3-fsp1, its proximity to the site entrance could suggest that the recorded soot traces could be natural. Unfortunately, there is a lack of experimental data related to the fixation, recording, and preservation of soot marks on cave entrance walls or rock shelters during natural fires (and the experimental data collected to date—Vandevelde *et al.*, 2023—unfortunately do not allow us to gauge the recording or non-recording of wildfire marks in speleothems).

Nevertheless, in this particular context, there are several arguments that support the hypothesis of "anthropogenic fire" as the most parsimonious explanation. The Orgnac 3 sequence has revealed evidence of burnt bones and lithic elements, with concentrations in archaeological levels 6 and 2 (Moncel *et al.*, 2005). Ash was observed during excavation, and hearths are mentioned in other levels (although they have not been described in detail—see Combier, 1967, and mentions in Combier's field notes and plans). For example, Combier identified two “foyers délavés” (“faded fireplaces”) in level 4b (Combier, 1967), and these were then confirmed via magnetic susceptibility by Laafar *et al.* (2008), who also identified a third hearth via magnetic susceptibility and micromorphology. The studied stratigraphic column is perpendicular (longitudinal Sect. 7/8—north face) to the section in which the Australia boulder is present (section shown in Fig. 2). The stratigraphic column is therefore located approximately 2 m away from the Australia boulder and the Org3-fsp1 speleothem. Micromorphological samples taken there show much charcoal and numerous burnt bones (Laafar *et al.*, 2008). Furthermore, at Orgnac 3, burnt elements (lithic and bone remains) are present in almost all levels, varying between 12.2 and 33.3% for lithic elements (Supplementary Note 10 online, Tables S5 and S6). Fire-related alterations take different forms in flint, ranging from light heating (reddish color) to intense heating (bluish to blackish color, thermal cupolas, cracks, *etc*.—Supplementary Note 10 online, Figure S15). In level 6, for example, where two possible fireplaces have been identified (corresponding to concentrations of burnt flint and bones associated with ashes), 23.3% of the lithic material corresponds to flakes, chunks, and thermal fragments such as cupolas. The highest percentage of burnt lithic elements can be found in level 5b (33.3%) and lowest (12.2%) in level 7. Heated or burnt bones represent between 0.8 and 4% of the coordinated material, with a peak in levels 4a, 5b, and 6 (Supplementary Note 10; Moigne, personal communication). It would be necessary to count the uncoordinated splinters from square sieving for a more accurate count, but this provides an indication of their distribution among long bones or large fragments.

The presence of fire remnants in an “enclosed site” (not an open-air location where fire can spread freely) with multiple traces of human activities serves as valuable indicators of fire use by hominins in various archaeological levels at the site. Note that the site functioned as a cave and then as a shelter following successive roof collapses during Complex III. These remnants are considered to be “good evidence of fire”, with a confidence index of 2 out of 3 according to the scale established by Roebroeks and Villa (2011).

Moreover, natural fires, often caused by lightning strikes, can occur in both warm and cold environments, but are more likely to happen in dry conditions with available biomass as fuel (Sorensen, 2017, and references therein; Dibble *et al.*, 2018). The documented soot traces are older than the fire evidence from archaeological level 2 and may be contemporaneous with the traces found in archaeological level 6 (if the speleothem formed on the ceiling before the fall of the “Australia” boulder). If Org3-fsp1 formed on the vault and registered fire events attributed to archaeological levels 6 or 5, then according to Michel *et al.* (2011), Orgnac 3’s climate was temperate and humid. In such warmer conditions, lightning strikes are more likely than in colder climates (Dibble *et al.*, 2018). Even in generally humid climates, natural fires can occur during dry periods. Alternatively, the soot traces could be somewhat more recent, possibly contemporary with hearths and burnt artifacts identified in archaeological level 4 (if the speleothem formed on the block after it fell to the ground). According to Michel *et al.* (2011), Orgnac 3’s archaeological level 4 corresponds to a cold and humid climate phase, and in these climatic conditions, natural fires caused by lightning strikes are less likely than during warmer periods (Dibble *et al.*, 2018). At a more local scale, we can identify dry or wet periods directly recorded in the Org3-fsp1 speleothem, reflected by the formation of micritic or micro-sparitic calcitic deposits (see the "Materials" section and Supplementary Note 6 online). Petrographic observations of the sample reveal that the soot marks resulting from fire events were not only associated with calcite formed during dry periods when natural fires can start and spread but were also associated with wet periods in 52% of cases, strongly supporting the hypothesis of non-natural fires at Orgnac 3 accounting for at least more than 50% of the cases.

The soot in the Org3-sp1 speleothem likely comes from archaeological levels 6 to 4, which show many signs of hearths and fire use. Given the evidence of human activity, the environmental conditions, the enclosed nature of the site, and the association of soot films with microsparite deposits formed during wet periods, the most likely and parsimonious hypothesis is that the soot traces in speleothem Org3-fsp1 are indeed remnants of anthropogenic fire. However, without further field analysis, it is difficult to definitively link these soot marks to the documented hearths in levels 6, 5, or 4. Nonetheless, these soot deposits provide the strongest and most well-documented evidence of repeated fire use on the site to date. The chronology of these soot films is well established, with at least five direct dates obtained in stratigraphy. Therefore, the record of many fire events (at least 23, possibly 27) at the Orgnac 3 site strongly supports Roebroeks and Villa's (2011) previous claim of "good evidence of fire" during MIS 9 and 8, which could now be updated to "clear evidence of fire" with a confidence index of 3/3.

A Habitual Use of Fire?

The recurrence of soot films in Org3-fsp1 speleothem, the presence of fire traces in the form of burnt bones and lithic material in archaeological layers 6, 5, and 4, and the identification of hearths in level 4 demonstrate the repeated use of fire by Middle Pleistocene hominins at Orgnac 3. However, it is important to clarify whether this use of fire was habitual.

The term "habitual use" generally refers to the repeated use of fire at a specific site or in a particular region over a period of several thousand years. For example, Roebroeks and Villa (2011) deduced the habitual use of fire by Pre-Neanderthals by counting the number of sites with strong evidence of fire throughout the Middle and Late Pleistocene. Some researchers (Shimelmitz *et al.*, 2014) also consider "habitual use" to imply planning, whereas "opportunistic use" is more occasional. On the other hand, for others (Shahack-Gross *et al.*, 2014), "habitual use" means the systematic and repeated use of fire in specific sites and/or regions. The interpretation of "habitual use" can vary among researchers, with some using terms like "regular", "persistent", "continuous", or "perpetual" as synonyms (Sandgathe, 2017). According to the authors, the term "habitual use" can therefore have a specific meaning, implying planning, regularity and high frequency of fire use, or on the contrary, a very broad meaning, implying no planning, which can include opportunistic use and "repeated" use on a multi-millennial scale.

Estimating the time between fire-use events (decades?, centuries?, millennia?) is a significant challenge (Herrejón-Lagunilla *et al*., 2024; Sandgathe, 2017). However, our new data allows us to discuss this notion by directly observing numerous soot traces that form a sequence of over 20 fire events at a single site. For the first time, our fuliginochronological study (including direct dating) of the Org3-fsp1 speleothem provides information on the actual frequency of fire use at the site: 23 to 27 fires occurred in the same sector in ca. 1000 years, around 270,000 years ago. This means there was a fire every 37 to 43 years (average: 1 fire every 40 years). The average time between fires at Orgnac 3 was therefore decadal. This Middle Pleistocene frequency is lower than that of more recent Upper Pleistocene sites in the same region, such as Grotte Mandrin (rock shelter, mid-Rhone Valley), where an average of 1 to 3 fires occurred per year (depending on the phase of occupation spanning between the Eemian and ca. 42,000 years ago) (Vandevelde, 2021, 2024). There are two ways to interpret this result: Either fire use on the site was rare (although an interval of 23 to 27 fires per 1000 years is already greater than what is typically considered "habitual" fire use) or occupations on the site were infrequent (around 1 occupation per 2 human generations). Although the high fire frequency at Orgnac 3 makes it impossible to determine whether fire was intentionally produced by the Mid-Pleistocene hominins who occupied the site or if its use was opportunistic with maintenance, it does indicate that this Middle Pleistocene site is an "example of long-term, successive use of fire" that can be interpreted as evidence of "habitual" fire use (as defined by Sandgathe, 2017).

Here we focus on a single site that provides clear evidence of long-term, successive, and controlled fire use during the Middle Pleistocene in Western Europe. These findings contribute to our understanding of fire use in the region and can now be included in broader studies on regional patterns of fire use.

Controlled Use of Fire: Maintenance and/or Ignition?

Whereas numerous studies have identified combustion structures and examined their role in spatial organization or fuel management choices, very few sites demonstrate regular fire use at the end of the Lower Paleolithic (Bentsen, 2020; Karkanas *et al*., 2007; Roebroeks & Villa, 2011). Although the use of natural fires by hominins, even in the Lower Paleolithic, is widely accepted (Scott & Hosfield, 2021), the issue of fire control, including ignition, by Neanderthals remains a topic of debate, even in more recent periods (Dibble *et al*., 2018; Sandgathe *et al*., 2011b). A recent study provides information on the use of "lighters" by Neanderthals during the Mousterian of Acheulean Tradition (MTA) technoculture ca. 50,000 years ago, but there is no evidence of such usage before this period (Sorensen *et al*., 2018). In other regions, no correlation has been found between the frequency of natural fires (indicated by light PAH—polycyclic aromatic hydrocarbon measurements) and the frequency of anthropogenic fires (indicated by heavy PAH); the latter correlates rather with artifact density at a site. These results suggest that pyrotechnology (referring here to the technology involved in fire production or long-term maintenance, rather than the use of fire as a tool) existed among Middle Paleolithic hominins during the Upper

Pleistocene, around 60,000 to 40,000 years ago, independent of environmental conditions and the availability of natural fires in the landscape (Brittingham *et al.*, 2019). The emergence of habitual fire use and the development of fire ignition control remain unresolved questions that continue to be explored by many researchers. The antiquity of these practices and the lack of sufficient cases with compelling evidence of fire control contribute to the ongoing unresolved nature of this issue.

The soot accumulation at Org3-fsp1 provides clear evidence of fire resulting from hominin behavior. However, it is possible that fire was acquired from natural sources rather than being created by hominins. Ethnography demonstrates that populations can maintain, store, and transport fire over extended periods of time. For instance, the Onges and Yuquí collect and maintain fire for as long as possible (McCauley *et al.*, 2020 and references therein), and other groups in the Americas have been documented carrying fire from one camp to another in portable forms such as firebrands, slow matches, or smoldering embers (McCauley *et al.*, 2020). Therefore, the presence of fire at Orgnac 3 could be attributed to individuals collecting naturally occurring fire and successfully preserving it. Although fire would be controlled in this scenario, the ability to produce it at will would be absent. Its use would be opportunistic (in the sense of Shimelmitz *et al.*, 2014) but not fortuitous (term used by James *et al.*, 1989), as it would rely on the technology necessary for maintaining fire over extended periods, as evidenced by its use during wet periods (cf.the "Natural or anthropogenic fire events?" section).

The Orgnac 3 case exemplifies the mastery of fire by Middle Pleistocene hominins at the site. This paper presents new and compelling evidence of fire's regular use at the transition between the Lower and Middle Paleolithic. The sole association of the soot films with calcite deposits formed during dry periods (micrite) would not allow discussion of fire ignition capacity: the fire traces in the cave could result from a fortuitous or opportunistic use of fire. However, when soot films are associated with calcite laminae formed during wet periods (microsparite), as is the case here, fire control can be argued, and it can be suggested that fire ignition might be controlled. Supporting this notion is the unlikelihood of harvesting natural fires during wet periods, especially on a regular basis, as indicated by the many cases of soot associated with sparitic deposits in Org3-fsp1. However, it is not currently possible to determine whether fire was controlled, harvested, and maintained or if it was controlled and produced at will, until direct evidence of fire-making technology is identified.

Traditionally, three stages of fire-use evolution are recognized: (i) fear or fascination, (ii) collection without production, and (iii) fire at will with ignition capacity (Harrison, 1954; Oakley, 1956; Oakley, 1961; Perlès, 1977). However, the most significant change is not the transition from one stage to another, but rather the shift from a life without fire to a life with fire, regardless of whether it was produced or not. This progress is psychological rather than purely technical. It entails a search for methods to maintain, conserve, and/or produce fire, requiring a reorganization of society to accommodate these new tasks (Perlès, 1977). Furthermore, it is unclear which is more laborious between production and conservation, particularly as reliance on the collection of natural fires means depending on randomly available resources. At the Orgnac 3 site, the presence of a sooty speleothem is direct evidence of the repeated use of fire around 270,000 years ago. Fire undeniably formed part of the technical and ethological repertoire of the Middle Pleistocene populations that occupied the site at that time. From a behavioral standpoint, this suggests that these Middle Pleistocene humans made a significant investment in using fire, whether it was controlled, harvested, maintained, or directly produced.

Conclusions

Research consistently shows that the use of fire and its technical applications are older and more extensive than previously thought. However, the archaeological record suggests a slow and irregular development in the use of fire (Perlès, 2024). For instance, there is debate about whether Quina-type Mousterian groups had the ability to use fire freely. Some argue that the scarcity of fire traces at these sites during cold phases reflects behavioral factors, whereas others attribute it to taphonomy (*e.g.*, Dibble *et al.*, 2018; Sorensen & Scherjon, 2018). Additionally, under some circumstances, there are ethnographic examples of groups using fire without producing it themselves, relying on neighboring groups instead (McCauley *et al.*, 2020). The case of Orgnac 3 provides site-specific evidence that fire was used habitually and controlled by humans in the Middle Rhone Valley during the Mid-Pleistocene. This information contributes to a broader understanding of the evolution, innovation, and diffusion of fire-related techniques.

In contrast to combustion structures, soot is well preserved in carbonates and is not significantly affected by taphonomic changes (see characterization analyzes in Supplementary Note 3 online). Therefore, fuliginous speleothems are ideal materials for studying ancient fire traces. These speleothems can be dated directly using methods like U-Th, making them valuable for investigating the Lower to Middle Paleolithic transition period. Fuliginochronology, along with other microscopic and chemical analysis methods such as sediment micromorphology and geophysical, spectroscopic, and geochemical analyses, further enhances the documentation of old fire evidence (*e.g.*, Brittingham *et al.*, 2019; Gallo *et al.*, 2023; Goldberg *et al.*, 2012, 2017; Herrejón Lagunilla *et al.*, 2019; Herrejón-Lagunilla *et al.*, 2024). A comprehensive search for and analysis of sooty speleothems on other ancient sites could help determine the natural or anthropogenic origin of fire in cases like the Caune de l'Arago at Tautavel, France. At this site, evidence of fire has been identified in an ancient level (Q4) dated around 560,000 years ago, but the nature of these traces remains to be investigated (Deldicque *et al.*, 2021).

This study is the first to highlight such a recurrence of fires at such an ancient site considering the minimum number of fire episodes and the time span: the Orgnac 3 sooty speleothem, Org3-fsp1, recorded a minimum of 23 occupation events with fire use, occurring during both wet and dry periods. Because the speleothem formed over approximately 1000 years, the frequency of this recurrence is estimated to be once every 40 years. The chronicle of Mid-Pleistocene occupations at Orgnac 3 has been reliably dated between 277,000 and 248,000 years ago, aligning with previous chronological studies (Bahain *et al.*, 2022). These dates contribute to solidifying the chronology of the transition between the Lower and Middle Paleolithic, enabling exploration of evolutionary questions.

In short, fuliginochronology has overcome the challenges of identifying the repeated use of fire on ancient and altered combustion structures. We used this approach to demonstrate that the fire traces found at the Orgnac 3 site were created by humans during the Mid-Pleistocene period. This evidence is the strongest and most well documented to date of European hominins' repeated use of fire during this time and over this ~1000 years time span. Our findings suggest that hominins had the ability to preserve and maintain fire at a minimum, but possibly were igniting firing at the site. This indicates that some form of pyrotechnology was part of the ancient population's toolkit at Orgnac 3. Additionally, the presence of soot traces can be used as an indicator of human occupation, even from the early Middle Paleolithic period in the Middle Rhone Valley. Therefore, fuliginochronology can provide valuable insights into the occupation dynamics of cave archaeological sites in this region from this early period.

Perlès wrote in 1977 (p. 153): "There is a profound difference between the richness that we perceive, and the poverty of what we really know about fire in the Paleolithic" (…) "[Fire] is only directly perceptible in the instant in which it burns: And it is only the effects of combustion that we can trace, never, of course, the combustion itself." *[« Il y a une différence profonde entre la richesse que nous percevons, et la pauvreté de ce que nous connaissons réellement du feu au Paléolithique» (…) « [le feu] n'est perceptible que directement que dans l'instant, celui où il brûle: et ce sont seulement les effets de la combustion que nous pouvons retrouver, jamais bien sûr la combustion elle-même.»]* (Perlès, 1977). With the study of sooty speleothems as an archaeological archive, it is finally also possible to recapture the moment and to explore the temporality of fire use.

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Author Contribution S.V. conducted the study and wrote the article. She carried out the petrographic and fuliginochronological analyses. E.P.-B. carried out the sample's dating. D.D. and S.V. undertook and interpreted the Raman analyses. D.S. and S.V. conducted the geochemical analysis, and A.N. performed the counting of annual cycles (under K.B. and S.V. supervision as part of his Master degree). C.M. studied the lithic material at Orgnac 3. Y.P. conducted the UV fluorescence analysis and counting of fluorescent laminae. B.D. participated in the elaboration of the strategy for calculating the confidence

scores, done by S.V. L.S. identified the black deposits as most likely soot and identified their potential for speleothem analysis. S.V., E.P.B., C.M., D.S., A.N., K.B., D.D., and Y.P. contributed to the writing of the supplementary notes and figures. All authors reviewed and enriched the paper.

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Data Availability Data is available in the main text or the supplementary materials (See supplementary notes online).

Declarations

Competing Interests The authors declare no competing interests.

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