



# The evolution of pyrotechnology in the Upper Palaeolithic of Europe

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## Abstract

Pyrotechnology, the ability for hominins to use fire as a tool, is considered to be one of the most important behavioural adaptations in human evolution. While several studies have focused on identifying the emergence of fire use and later Middle Palaeolithic Neanderthal combustion features, far fewer have focused on modern human fire use. As a result, we currently have more data characterizing the hominin fire use prior to 50,000 years before present (BP), than we do for Upper Palaeolithic of Europe. Here we review the available data on Upper Palaeolithic fire evidence between 48,000 and 13,000 years BP to understand the evolution of modern human pyrotechnology. Our results suggest regional clustering of feature types during the Aurignacian and further demonstrate a significant change in modern human fire use, namely in terms of the intensification and structural variation between 35,000 and 28,000 years BP. This change also corresponds to the development and spread of the Gravettian technocomplex throughout Europe and may correspond to a shift in the perception of fire. Additionally, we also show a significant lack of available high-resolution data on combustion features during the height of last glacial maximum. Furthermore, we highlight the need for more research into the effects of syn- and post-depositional processes on archaeological combustion materials and a need for more standardization of descriptions in the published literature. Overall, our review shows a significant and complex developmental process for Upper Palaeolithic fire use which in many ways mirrors the behavioural evolution of modern humans seen in other archaeological mediums.

**Keywords** Pyrotechnology · Upper Palaeolithic · Modern humans · Fire Use · Europe

## Introduction

The ability to harness, use and create fire is among the most important developments in human evolution. Alongside systematic stone tool production, bipedalism and encephalization, the development of fire as a tool (i.e. pyrotechnology) is seen as a fundamental and defining hallmark of the genus *Homo*. In current societies, fire use has developed into an essential part of daily life, taking a vitally important role as both a natural and cultural resource. Given fire's importance to the biological and social evolution of our species, its unsurprising that studies into Palaeolithic fire use have been near the forefront of Paleoanthropological research over the last few decades. Yet, even with the current advancements in methods and the publication of new data related to fire use

(e.g. Brittingham et al. 2019; Mallol et al. 2013b; Mentzer 2014), there remains fundamental gaps in current understanding of the evolution of pyrotechnology. We particularly know relatively little of how pyrotechnology evolved, that is, how combustion features were constructed, used and maintained, and how these structures vary morphologically through time and across different regions.

In the last decade, a renewed interest in fire studies from Neanderthal contexts has led to increased research into Middle Palaeolithic fire features (Brittingham et al. 2019; Leierer et al. 2020; Roebroeks and Villa 2011), their nature (Aldeias et al. 2012; Courty et al. 2012; Leierer et al. 2020) and absence at certain times and regions of Europe (Dibble et al. 2018; Goldberg et al. 2012; Sandgathe et al. 2011). While these discussions often rest on a dichotomy between Neanderthals and early Anatomical Modern Humans (AMH) in Europe, there has been surprisingly far less research dedicated to characterizing fire use by AMH during the Upper Palaeolithic. This paper aims to fill this research gap by reviewing available data on the evolution of pyrotechnology in European Upper Palaeolithic archaeological contexts.

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## Pyrotechnology in Palaeolithic archaeology

The evolution of hominin fire use in the Pleistocene has generally been divided into three phases: 1) opportunistic use of fire sourced from natural contexts (e.g. wildfires, lightning strikes, etc.), 2) control of fire via refuelling, transport and restraint, and 3) production of fire by artificial means (Chazan 2017; Sandgathe 2017; Stahlschmidt et al. 2015). The use of this framework has driven research into fire use to be overwhelmingly focused on either the origins of fire-related behaviour in hominin evolution (Berna et al. 2012; Chazan 2017; Gowlett 2016; Hlubik et al. 2019; Lebreton et al. 2018; MacDonald et al. 2021; Sandgathe 2017; Stahlschmidt et al. 2015; Wrangham 2017) or the development and habitual use of pyrotechnology by Neanderthals in the Middle Pleistocene of Europe (Albert et al. 2012; Aldeias et al. 2012; Brittingham et al. 2019; Dibble et al. 2017; Goldberg et al. 2012; Goldfield et al. 2018; Mallol et al. 2019b; Rigaud et al. 2015; Roebroeks and Villa 2011; Rosell and Blasco 2019; Sandgathe et al. 2011). By the time the Upper Palaeolithic appears in Europe ~45 thousand years before present (ka BP) (Fewlass et al. 2020b; Hublin et al. 2020), fire use is considered to be ubiquitous and a fundamental part of AMH daily life (Chazan 2017; Pryor et al. 2016; Roebroeks and Villa 2011).

Regardless of period, however, the recognition of anthropogenic fire is not always straightforward, as fire remnants can be derived from both natural sources and human agency (Goldberg et al. 2017; Mallol et al. 2017; Stahlschmidt et al. 2015). Much of the evidence we have for early fire use in the archaeological record, i.e. the first two phases mentioned above, is based on interpretations of indirect proxies (e.g. heated lithics, charred bone and reddened sediments) found associated with archaeological assemblages. There are several sites for which the presence of fire prior to 400 ka BP has been proposed (Berna et al. 2012; Gowlett and Wrangham 2013; Stahlschmidt et al. 2015), though they remain few and far between. After 400 Ka BP, the direct evidence of anthropogenic fire use in the form of combustion features, while still very limited, is more apparent within the archaeological record (Roebroeks and Villa 2011; Sandgathe 2017; Sandgathe et al. 2011). It is not until the late Middle and Upper Palaeolithic that combustion features become more common within archaeological assemblages (Roebroeks and Villa 2011).

Combustion features—use here as more general term to describe both well-preserved hearths and fire remnants in secondary contexts (Aldeias et al. 2012; Mentzer 2014)—are the primary evidence to understand the evolution of pyrotechnology, as they are sedimentary artefacts with a structural variation formed directly from human action (Mentzer 2014; Miller 2011). The detailed descriptions of

the morphology and composition of combustion features, i.e. their shape, components and context, are invaluable sources of paleoenvironmental information (Mallol and Henry 2017; Miller 2011; Stahlschmidt et al. 2020) (e.g. type of fuel used), as well as for reconstructing hominin behaviour and culture. The evidence of fire has been evaluated using different proxies including: burned bones (Costamagno et al. 2009; Gallo et al. 2021; Théry-Parisot 2002; Théry-Parisot et al. 2005), charcoals (Lebreton et al. 2018; Théry-Parisot et al. 2010; Théry-Parisot and Henry 2012), heat-altered lithics (Abdolahzadeh et al. 2022; Playšić et al. 2020), as well as via ethnographic (Friesem 2016; Mallol and Henry 2017) and experimental data (Aldeias et al. 2016). Identifiable combustion features are commonly interpreted as a hub for domestic, social and cultural activities taking place during human occupations. Understanding how the morphology of these features evolves in the archaeological record is an essential, yet often underutilized, resource for studying variations in human behaviour through time.

There have been several recent studies of Middle Palaeolithic fire use covering various aspects of Neanderthal combustion features including their components, the timing and intensity of use, as well as the potential for complex uses of fire beyond cooking, warmth and light (Brittingham et al. 2019; Jambrina-Enríquez et al. 2019; Leierer et al. 2020, 2019; Mallol et al. 2019a, 2013a; Pérez et al. 2017; Roebroeks and Villa 2011). There are also considerable debates concerning whether Neanderthals were habitual fire users, i.e. capable of not only controlling but also producing fire via artificial means (Brittingham et al. 2019; Dibble et al. 2018). The current evidence of fire use at Middle Palaeolithic sites suggests Neanderthals primarily built flat, unlined combustion features (Leierer et al. 2020, 2019; Mallol et al. 2013b; Marcazzan et al. 2022), though there is also limited evidence for the potential use of pit features, i.e. combustion features within artificially dug depressions (Mallol et al. 2017), at the sites of El Salt in Spain (Leierer et al. 2020) and of Kebara and Hayonim in Israel (Albert et al. 2012; Goldberg and Bar-Yosef 2002; Meignen et al. 2007). It has also been recently suggested that Neanderthal's use of pyrotechnology and adaptations towards fire use potentially varied regionally (Brittingham et al. 2019; Dibble et al. 2017, 2018). Overall, these results have shown that the Neanderthal record for fire use is much more complex and diverse than previously thought. Despite these efforts, we still lack larger-scale studies and detailed datasets on variations in the morphology (e.g. shape) of Neanderthal combustion features to better understand how Neanderthal pyrotechnology changed through time (Leierer et al. 2020).

The lack of detailed studies is even more pronounced in available data for combustion features on Upper Palaeolithic sites in Europe. The European Upper Palaeolithic is commonly associated with the appearance of AMH and marks

a major change in terms of behaviour and material culture compared to the Middle Palaeolithic. The earliest evidence of Upper Palaeolithic AMH comes from the Initial Upper Palaeolithic (IUP) materials and human remains recovered from Bacho Kiro cave dating to around 45 ka BP (Fewlass et al. 2020b; Hublin et al. 2020; but see Slimak et al. 2022). The IUP is represented by several so-called transitional lithic industries found throughout Europe, around which there is considerable debates over their authorship (Hublin 2015). The IUP was followed by the Early Upper Palaeolithic (EUP) which is generally associated with the Aurignacian technocomplex starting around 43 ka BP (Higham et al. 2012; Nigst et al. 2014). The Aurignacian is widely considered to be the first pan-European Upper Palaeolithic technocomplex, with the evidence of Aurignacian materials found at sites across Europe (Bolus and Conard 2001). The subsequent Middle Upper Palaeolithic (MUP) starting roughly ~34 ka BP (Moreau et al. 2016) seems to represent a major transition in terms of AMH mobility and occupational patterns with the establishment of longer-term settlements such as those found at the Pavlovian Hills sites of Dolní Věstonice I and II, Pavlov I-IV and Milovice I-IV (Beresford-Jones et al. 2010; Fewlass et al. 2019; Pryor et al. 2016; Svoboda 2013, 1997; Svoboda et al. 2015, 2016; Verpoorte 2000). The MUP is commonly associated with another pan-European technocomplex, the Gravettian (Kozłowski 2015). The Gravettian technocomplex, along with changes in lithic tools and behaviours, includes the first evidence of ceramic plastic production and fired loess objects (Farbstein and Davies 2017; Simon et al. 2014; Svoboda 2007; Vandiver et al. 1989). The end of the MUP coincides with the major climatic deterioration and harsh conditions of the Last Glacial Maximum (LGM) between 26.5 and 19 ka BP (Clark et al. 2009; Hughes and Gibbard 2015). It is widely agreed that the onset of the extreme cold conditions and loss of habitable areas throughout the northern latitudes of Eurasia led to changes in human behaviour and population dynamics (Gautney and Holliday 2015; Moreau et al. 2021; Pinhasi et al. 2014; Škrdla et al. 2021; Straus 2015; Wilczyński et al. 2021). This includes the creation of relatively short-lived and more regionally isolated technocomplexes, like the Solutrean, Magdalenian and Epi-Gravettian as well as others, concentrated in so-called refugia regions (Leesch et al. 2012; Nerudová and Neruda 2015; Šída et al. 2021; Straus 2012; Street et al. 2012; Wiśniewski et al. 2017).

In terms of fire-related evidence, while it is widely accepted that AMH had the ability to create, maintain and use fire in complex ways; the evolution of fire as a technology in the Upper Palaeolithic (henceforth UP) has remain vastly unexplored. Most of the current studies into UP fire use and pyrotechnology have focused on individual sites (Bosch et al. 2012; Braadbaart et al. 2020; Fladerer et al. 2014; Karkanas et al. 2004; Schiegl et al. 2003; White et al.

2017) or variations in hearth components like fuel sources (Buonaserà et al. 2019; Costamagno et al. 2009; Henry and Théry-Parisot 2014; Marquer et al. 2010; Théry-Parisot et al. 2005; Yravedra et al. 2016; Yravedra and Uzquiano 2013). Moreover, the wide methodological variety in excavation strategies, sampling methods, descriptions and regional research biases has further limited larger-scale reviews of UP pyrotechnology. As a result, we currently have more data available for discussing the origins of fire use and Neanderthal fire use than we do about the development of AMH pyrotechnology in the last 50 ka BP. To fill this research gap, we review the evolution of pyrotechnology in the Upper Palaeolithic of Europe, collecting data from published macroscopic field observations of Upper Palaeolithic combustion features to characterize the nature of fire features and identify possible patterns in the evolution of modern human pyrotechnology.

## Methods

We have conducted a comprehensive literature review of published descriptions of UP sedimentary combustion features between ~47,5 ka and ~13 ka BP. For the guidelines for our review, we adhered to FAIR (Findability, Accessibility, Interoperability, Reusability) guiding principles for scientific data management and stewardship, commonly used in the natural sciences (Wilkinson et al. 2016). Data was collected from May 2019 until July 2022 using open access or widely accessible online repositories and search engines, including Google Scholar, Web of Science, Academia and ResearchGate. We conducted our search for publications using keywords, such as fire, combustion, hearths, charcoal, burning, fireplace and thermal alteration, in English, French, German, Portuguese and Spain.

Our primary temporal focus was the EUP and MUP of Europe, where we conducted a systematic review of published descriptions of fire residues associated with the Aurignacian and Gravettian Technocomplexes. We then expanded our analysis to encompass IUP sites, which includes “transitional UP lithic industries” (e.g. Châtelperronian, Szeletian, Bohunician, Skreletskian, Spitsynian), as well as well-documented combustion features associated with Late MUP and Late UP technocomplexes, i.e. Solutrean, Magdalenian and Epi-Gravettian assemblages to better integrate our data into more general patterns during the Upper Palaeolithic. For both the IUP and Late UP, we focused mainly on the results from our keyword searches for sites where combustion features were directly mentioned in the available literature. In our subsequent analysis, we used the cultural attributions provided by the respective author(s) and do not attempt to interpret or assign cultural affinity any further. Discussions over more regional technocomplexes and industries found

throughout the UP are beyond the scope of this paper. Geographically, we restricted our review to the available data from sites with UP combustion features spanning Central, Eastern Europe (Ukraine, Western Russia, Moldova, Serbia, Croatia, Romania, Poland, Slovenia, Slovakia, Hungary, Greece, Czech Republic, Austria and Germany) and Western Europe (France, Spain and Portugal).

Due to the lack of standardized methodologies to ascertain the nature, spatial dispersion and degree of burned in components, we focused primarily on comparative data from published constrained combustion features. As defined by Mallol et al (2017), contained combustion features refer to anthropogenically controlled burning confined by either the lateral placement of fuel or structural elements. We also collected data on non-contained anthropogenic combustion features, i.e. ash dumps, as well as presence of portable light sources, when such data was available. However, the use of lamps and portable light sources is outside the scope of this paper.

Our objective throughout our review was to collect as much detailed information about individual combustion features as possible. Since the level of detail and descriptions of combustion features vary greatly from site to site and from publication to publication, we classified sites that we reviewed into three categories based on the descriptive resolution available:

- Category 1: presence of combustion features, but indirect or limited data available.
- Category 2: available direct data with detailed field descriptions of some/all of combustion features identified at the site.
- Category 3: Detailed field descriptions with available microcontextual data of combustion features.

The list of sites and classifications are presented in the SI (SI 1). Category 1 refers to sites in which there is evidence to suggest burning was present (*e.g.* mentions to burned lithics, reworked charcoal remains, etc.), but lack more detailed descriptions. Category 1 also encompasses sites in which combustion features were referred to indirectly, either as part of a summary or review paper, or as present within context of other material culture. Category 2 refers to sites where there were available detailed field descriptions of some/all the combustion features present within the site or from multiple layers within the site. Finally, Category 3 includes datasets where detailed macroscopic observations are published alongside archaeological soil micromorphological and/or geochemical analysis of the some/all of combustion features present. While depending solely on field descriptions can be problematic (Leierer et al. 2020), the availability of microcontextual descriptions using archaeological soil micromorphology and geochemical analysis can give

invaluable information related to the formation, composition and function of combustion features that would otherwise be inaccessible based on field descriptions alone.

Using detailed field descriptions available from Categories 2 and 3 sites, therefore, we compiled the available data on individual combustion feature within the site/layer (SI 2). We collected and organized the data based on the following criteria: rate of recurrence of features per site and per layer; description of feature shape and dimensions; presence and nature of: ash (white layer), burned topsoil/charcoal-rich base (black layer) and heated substrate (commonly reddened layer); presence of superimposed fire events (*e.g.* stacking); nature of combustion feature microstratigraphy and contents (*i.e.* ash, charcoal, char, phytoliths, burned bones, burned lithics); and the interpreted degree of preservation of each feature.

Since shape is one of the descriptors available for most features, we then used our collected data to group many of the contained combustion features into a structural typology based on the nomenclature proposed by Mallol et al. (2017). When available, we also used the existing classification published by the respective author(s) as they fit within the typological definitions we used in our analysis. These features were classified into 4 distinct types: open flat hearths; pit structures; prepared burning surfaces; and fire installations.

Detailed description for each type is included in the results section below. Graphs were produced in R Studio (Team 2021) using the ggplot and tidyverse packages. The dates used in our analysis were calibrated with OxCal 4.4 program using the InCal20 calibration curve with a 95.4% probability (Bronk Ramsey 2009; Reimer et al. 2020) We used the median dates calculated using the to and from dates calculated in OxCal to produce our results.

## Results

We collected data on combustion features from a total of 164 UP sites. Of these, 109 of the sites reviewed were classified into category 1 as shown below in Table 1. As stated above this denotes the presence of combustion features or residues but with very limited or no data available related to the structure, composition and context of the features. Category 2 includes 44 sites with available field descriptions and observations related to some, if not all, the combustion features present at the sites. Finally, only 11 UP sites we reviewed had published detailed analysis of combustion features along with additional micromorphological and geochemical analysis and these sites were assigned to Category 3.

As our primary temporal focus was on the EUP and MUP, most of our data comes from sites with combustion features associated with Aurignacian ( $n = 59$ ) and Gravettian

**Table 1** List of Category 1 sites reviewed, where MP—Middle Palaeolithic, IUP—Initial Upper Palaeolithic, Boh—Bohunician, Sze—Szeletian, Chat—Châtelperronian, ProtoAu—Proto Aurignacian, Au—Aurignacian, EpiAu—Epi-Aurignacian, Gra—Gravettian, Per—Périgordian, Grav-Sol—Gravettian-Solutrean, Sol—Solutrean, Sol-Grav—Solutreo-Gravettian, Mag—Magdalenian, EpiGra—Epi-Gravettian. Sites ranked as categories 2 and 3 are discussed in the text and plotted in Figs. 2, 4 and 5

Site Name	Country	Fire Present	Reference
1 Langmannersdorf	Austria	EpiAu	(Salcher-Jedrasiak et al. 2010; Verpoorte 2004)
2 Saladorf/ Perschling	Austria	Gra	(Simon and Einwögerer 2008)
3 Ollersdorf	Austria	Gra	(Antl-Weiser 2008)
4 Alberndorf	Austria	Late Au	(Steguweit and Trnka 2008)
5 Berdyzh	Belarus	Gra	(Klein 1974; Soffer 1985)
6 Siuren I	Crimea	Au	(Demidenko and Otte 2000; Demidenko et al. 2012)
7 Stránská skála	Czechia	Au	(Svoboda 2006; Svoboda and Bar-Yosef 2003; Tostevin 2003; Valoch 2013)
8 Líšeň I/ Líšeň—Čtvrťe	Czechia	Au	(Demidenko et al. 2017; Škrdla 2017; Škrdla et al. 2016)
9 Vedrovice V	Czechia	Au	(Demidenko et al. 2017; Oliva 1989a; Škrdla 2017; Škrdla et al. 2016)
10 Líšeň VIII / Líšeň—70 yr výhonem	Czechia	Au	(Škrdla 2017; Škrdla et al. 2016)
11 Podoli V	Czechia	Au	(Demidenko et al. 2017; Škrdla 2017; Škrdla et al. 2016)
12 Napajedla III	Czechia	Au	(Demidenko et al. 2017; Škrdla 2017)
13 Mladec cave	Czechia	Au	(Svoboda 2001; Teschler-Nicola 2007)
14 Orzechov IV	Czechia	Boh	(Škrdla 2017; Škrdla et al. 2016)
15 Předmostí	Czechia	Gra	(Beresford-Jones et al. 2010; Svoboda et al. 2013)
16 Milovice I	Czechia	Gra	(Brugère et al. 2009; Oliva 1989b; Svoboda et al. 2005)
17 Kulna Cave	Czechia	Mag	(Neruda 2017)
18 Balcarka Cave	Czechia	Mag	(Moník et al. 2019)
19 Moravsky Krumlov IV	Czechia	MP, Sze	(Neruda and Nerudová 2010)
20 Pod Hradem	Czechia	MP, Sze, Au	(Nejman et al. 2018, 2017)
21 Isturitz	France	Au	(Barshay-Szmidt et al. 2018; Szmidt et al. 2010; Villa et al. 2002)
22 La Quina-Aval	France	Au	(Verna et al. 2012)
23 Grotte XVI	France	Au	(Karkanas et al. 2002)
24 Le Piage	France	Au	(Bordes et al. 2006; Costamagno et al. 2009; Villa et al. 2002)
25 Brassempouy Grotte des Hyenes	France	Au	(Henry-Gambier et al. 2004; Villa et al. 2002)
26 Caminade-est	France	Au	(Bordes 2000; Laville and de Sonneville-Bordes 1967; Villa et al. 2002)
27 Brassempouy Grotte du Papes	France	Au	(Henry-Gambier et al. 2004)
28 Abri Blanchard	France	Au	(White et al. 2017)
29 le Trou de la Chèvre à Bourdeilles	France	Au	(Villa et al. 2002)
30 Grotte Tournal	France	Au	(Villa et al. 2002)
31 Flageolet I	France	Au, Gra	(Rigaud et al. 2016; Simek 1984; Villa et al. 2002)
32 Chauvet Cave	France	Au, Gra	(Salmon et al. 2020; Théry-Parisot et al. 2018)
33 Abri du Facteur	France	Au, Gra	(White et al. 2017)
34 La Tuto De Camalhot	France	Au, Gra	(Bon 2002)
35 Quincay	France	Chat	(Lévêque 1979; Lévêque 1997; Lévêque and Miskovsky 1983; Roussel and Soressi 2010)
36 Abri de la Souquette	France	EUP	(White et al. 2017)
37 Roc de Combe	France	Gra	(Grayson and Delpech 2008; Zilhão and d'Errico 1999)
38 Arcy sur Cure, Grotte du Rennes	France	Gra	(Villa et al. 2002)
39 La Vigne Brun	France	Gra	(Digan 2008)
40 La Picardie	France	Gra	(Delvigne et al. 2020; Klaric et al. 2018)
41 Laugerie-Haute	France	Gra-Sol	(Schmidt and Morala 2018; Verpoorte et al. 2019)
42 Roc-aux-Sorciers	France	Mag	(Bourdier 2013)
43 Combe Sauniere IV	France	Sol	(Villa et al. 2004)
44 Le Cuzoul de Vers	France	Sol	(Ducasse et al. 2014; Villa et al. 2002)
45 Chauvet-Pont d'Arc	France	Au	(Salmon et al. 2020)
46 Bockstein	Germany	Au	(Bolus 2015)

Table 1 (continued)

Site Name	Country	Fire Present	Reference
47 Vogelherd	Germany	Au	(Niven 2007)
48 Hohlenstein-Stadel	Germany	Au	(Bolus 2015)
49 Sirgenstein	Germany	Au	(Bolus 2015)
50 Breitenbach—Schneidemuhle	Germany	Au	(Moreau 2012)
51 Lommersum	Germany	Au	(Bosinski et al. 1995)
52 Friedrichsdorf-Seulberg	Germany	Au	(Moreau and Terberger 2019)
53 Wiesbaden-Igstadt	Germany	Au	(Street and Terberger 1999)
54 Remagen-Schwalbenberg	Germany	EUP	(Bosinski et al. 1995)
55 Koblenz-Metternich	Germany	Gra	(Bosinski et al. 1995)
56 Sprendlingen	Germany	Gra	(Bosinski et al. 1995)
57 Mainz-Linsenberg	Germany	Gra	(Bosinski et al. 1995)
58 Brillenhohle	Germany	Gra, Mag	(Conard and Bolus 2003)
59 Munzingen	Germany	Mag	(Bosinski et al. 1995)
60 Oelknitz 3	Germany	Mag	(Gaudzinski-Windheuser 2012, 2015)
61 Gönnersdorf	Germany	Mag	(Street et al. 2012)
62 Andernach-Martinsberg	Germany	Mag	(Bosinski et al. 1995; Street et al. 2012)
63 Alsdorf	Germany	Mag	(Bosinski et al. 1995)
64 Istállóskő Cave	Hungary	Au	(Patou-Mathis et al. 2016)
65 Szeleta Cave	Hungary	Sze, Au	(Lengyel et al. 2016)
66 Riparo Mochi	Italy	ProtoAu	(Frouin et al. 2022; Holt et al. 2019)
67 Cosautsi	Moldova	EpiGra	(Haesaerts et al. 2003)
68 Deszczowa Cave	Poland	Au	(Wojtal 2007)
69 Dziadowa Skala	Poland	Gra	(Wojtal 2007)
70 Jaksice II	Poland	Gra	(Wilczyński et al. 2015)
71 Klementowice	Poland	Mag	(Wiśniewski et al. 2012; Wojtal 2007)
72 Nietoperzowa Cave	Poland	MUP	(Krajcarz et al. 2018; Wojtal 2007)
73 Lapa do Anecrial	Portugal	Gra	(Brugal 2006)
74 Cardina 1	Portugal	Gra	(Bergadà 2009)
75 Foz do Medal	Portugal	Gra	(Gaspar et al. 2016)
76 Olga Grande	Portugal	Gra	(Aubry 1998; Aubry and Sampaio 2003a, b; Sellami 2009)
77 Romanesti-Dumbravita I	Romania	Au	(Schmidt et al. 2013)
78 Mitoc Malu Galben	Romania	Au, Gra	(Nigst et al. 2021; Noiret and Otte 2010)
79 Tibrinu	Romania	EpiGra	(Anghelinu et al. 2018; Carciumaru et al. 2010)
80 Kostenki 1	Russia	Au?	(Hoffecker et al. 2016; Holliday et al. 2007)
81 Sungir	Russia	EUP	(Soldatova 2019)
82 Kostenki 12	Russia	EUP	(Anikovitch et al. 2007)
83 Borschevo 5	Russia	Gra	(Lisitsyn 2015)
84 Kostenki 13	Russia	Gra	(Sinitsyn and Sanz 2015)
85 Kostenki 11	Russia	Gra	(Pryor et al. 2020; Sinitsyn and Sanz 2015)
86 Kostenki 4	Russia	Gra	(Sinitsyn and Sanz 2015; Zheltova 2015)
87 Kostenki 8	Russia	IUP	(Sinitsyn and Sanz 2015)
88 Trabula Traiana Cave	Serbia	EUP	(Borić et al. 2012)
89 Bukovac Cave	Serbia	Gra	(Dogandžić et al. 2014)
90 Velika Pecina	Serbia	Gra	(Kuhn et al. 2014; Stiner et al. 2022)
91 Tibava	Slovakia	Au	(Svoboda and Simán 1989)
92 Barca II	Slovakia	Au	(Svoboda and Simán 1989)
93 Moravany-Lopata	Slovakia	Gra	(Pawlikowski et al. 1998)
94 Trencianske Bohuslavice	Slovakia	Gra	(Kaminská 2016; Vlačičky et al. 2013)
95 Potocka Zijalka	Slovenia	Au	(Verpoorte 2012)
96 Cova Foradada	Spain	Au	(Morales et al. 2019)

**Table 1** (continued)

Site Name	Country	Fire Present	Reference
97 Cueva Morin	Spain	Au, Gra	(Bradtmöller 2015; Bradtmöller et al. 2016)
98 El Castillo	Spain	Au, Gra	(Bernaldo de Quirós et al. 2015; Wood et al. 2018)
99 Finca Dona Martina	Spain	Gra	(Angelucci et al. 2018)
100 Coimbre Cave	Spain	Gra	(López-Cisneros et al. 2019; Yravedra et al. 2016)
101 Cueva Ambrosio	Spain	Sol	(López et al. 2015)
102 Pena Capon	Spain	Sol	(Alcaraz-Castaño et al. 2019)
103 Dobranichevka	Ukraine	EpiGra	(Klein 1974)
104 Mira	Ukraine	EUP	(Stepanchuk 2005)
105 Doroshivtsi III	Ukraine	Gra	(Kulakovska et al. 2015)
106 Mezin	Ukraine	Late Gra	(Klein 1974)
107 Puchkari I	Ukraine	Late Gra	(Klein 1974)
108 Lipa I	Ukraine	Late Gra	(Klein 1974)
109 Beregovovo	Ukraine	ProtoAu	(Usik et al. 2014)

( $n=67$ ) layers compared to the other cultural associations covered by our review. Several sites ( $n=19$ ) have multiple occupation periods associated with different UP technocomplexes. These sites consist namely in long sequences such as Abri Pataud, Cova Gran de Santa Linya, Lapa de Picareiro, among others. Figure 1 shows the distribution of the sites classified as categories 2 and 3 based on published cultural association(s).

As shown in Fig. 1, most of the sites classified as category 3 are related to Aurignacian ( $n=4$ ) and Magdalenian ( $n=4$ ) combustion features. Of the 67 sites reviewed with evidence of fire use in Gravettian layers, only 2.7% had available micromorphological data, while for Aurignacian layers, 6.7% had micromorphological data on combustion features. Based on the data available during our review, we found no currently published category 3 data for Epi-Gravettian.

Geographically, the reviewed sites range from the eastern European steppe in Russia to the Iberian Peninsula to the West. As shown in Fig. 2, most of the sites we identified could only be classified into our category 1 (blue symbols), which corresponds to sites where there is a mention of combustion features or burned remains but lack published detailed descriptions. Datasets of category 3, with detailed macroscopic observations alongside higher-resolution analysis of the formation history of combustion features (purple symbols), remain particularly rare.

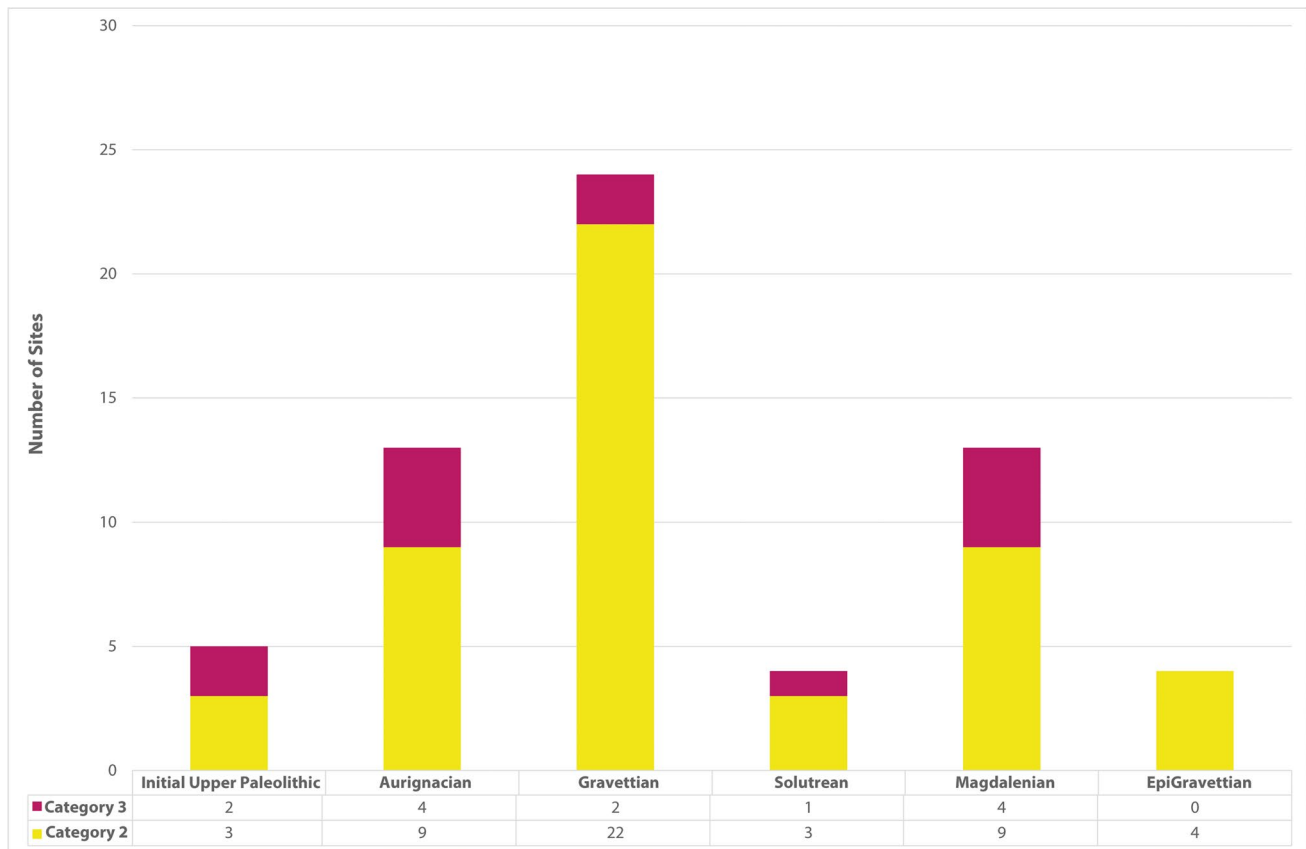
Despite recent efforts (Goldberg and Aldeias 2016; Goldberg et al. 2017; Miller 2011) to highlight the need for these types of microcontextual studies, this small number of well-described datasets clearly reflects a lack of studies specifically addressing pyrotechnological data for the UP in Europe. Without such information, many of the patterns on variability and change of pyrotechnology during the UP remain elusive. Another aspect that we noted during our review is the lack of standardization on how combustion

remains and features are published across the available literature. Simple descriptive characteristics such as the size, thickness and form of a given combustion features are not always reported, and more detailed information related to the presence of certain types of components such as wood and bone fuels, burned stones or presence of ash is exceptionally rare and context specific.

With the currently available data, we can note that, while the early to middle UP are characterized by pan-European technocomplexes, like the Aurignacian and Gravettian, there are large geographical voids in the available data. For instance, apart from very few Gravettian examples in Portugal there are little or no well-described combustion features for the Aurignacian and Gravettian in Iberia. This is in contrast with Magdalenian and Solutrean combustion features, with several examples of well-described sites in Iberian contexts (Badal et al. 2019; Fullola et al. 2012; Lucena et al. 2013; Villaverde et al. 2019). A cluster of well-described features for the Magdalenian is also present in north-eastern France (Wattez 1994). Particularly rich clusters of well-described datasets (category 2 and 3 sites) in the Périgord region of southern France and the Catalonia region of north-eastern Spain are shown in Fig. 2b. Most of Gravettian category 2 data comes from sites in the Middle Danube region of Central Europe (Fig. 2c) which includes parts of Austria, Czechia and Slovakia. The later UP is divided into more region specific technocomplexes with the Solutrean located in southwestern Europe, the Magdalenian in the western and central Europe, and the EpiGravettian in central and eastern Europe, respectively.

### Variations in feature types during the UP

We were able to collect morphological information on 133 combustion features using field descriptions from categories



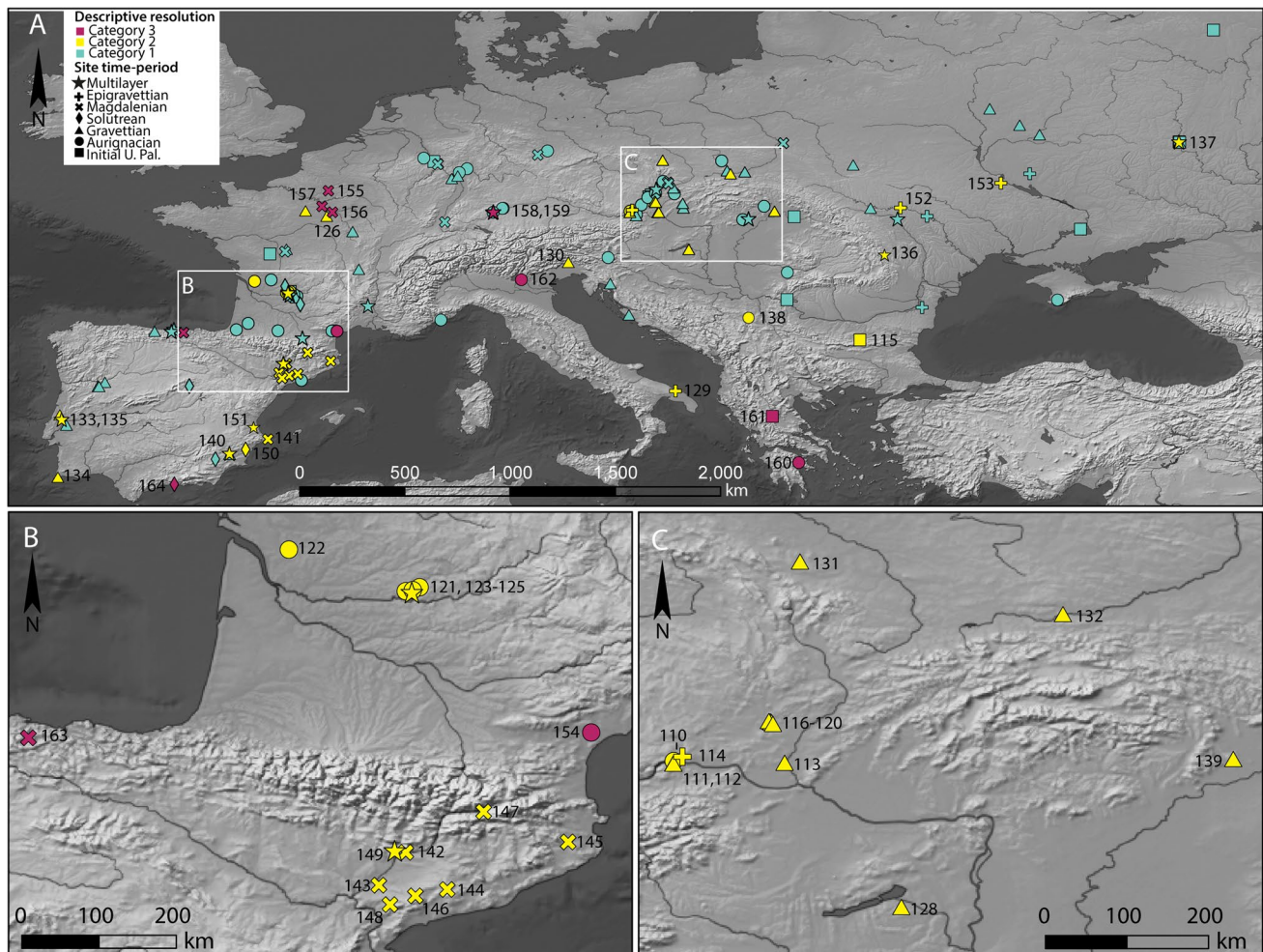
**Fig. 1** Distribution of categories 2 and 3 sites and cultural associations of fire evidence. Sites with fire evidence associated with multiple techno-complexes appear more than once

2 and 3 sites. We used this information to assign these features into types, specifically open flat hearths, pit structures, prepared burning surfaces and fire installations (Mallol et al. 2017), with some examples of these features types shown in Fig. 3. In addition to assigning features to specific types, we can also see variations in the chronological distribution of the four types of contained features through time (Fig. 4). Our results demonstrate a pattern of relative increase of diversity in the types of combustions features found in UP assemblages between 36 and 28 ka cal BP. Most of the well-described combustion features we collected data for fit within this timeframe. As we expanded our review into the LGM and Late UP, our results indicate a considerable gap in well-described features between 28 and 18 ka cal BP. It was only in the late UP where we recovered data from several combustion features dated between 18 and 13 ka cal BP. Below, we outline patterns and observations for each of the four contained combustion feature types found on UP sites, starting with open flat hearths.

**Open flat hearths** Open flat hearths are simple combustion structures placed over a relatively flat and unprepared substrate (Mallol et al. 2017). Open flat hearths are prevalent

throughout the UP across Europe—though they might be underrepresented in this analysis since they are seldomly well described in the available literature. Similar to types of combustion features commonly found within Neanderthal contexts, the earliest UP combustion features tend to be simple flat hearths. The earliest evidence for UP flat combustion features appears in Eastern Europe, namely at Kostenki 14 (Russia) Horizon of Hearths, which consists of several discrete overlapping lenses of intensely burned loam with charcoal (Hoffecker and Anikovich 2014; Holliday et al. 2007; Sinitsyn 2004). This Horizon of Hearths was dated by optically stimulated luminescence (OSL) to between 47.8 and 40.1 ka BP (Hoffecker and Anikovich 2014; Holliday et al. 2007). At the IUP site of Bacho Kiro (Bulgaria), several flat hearths were described within Layer 11 (Kozłowski 1982). These features vary in size between 35 and 75 cm in diameter (Kozłowski 1982) and date between 44.5 and 43.2 ka cal BP (Fewlass et al. 2020a) (Recalibrated using Oxcal 4.4).

Throughout the UP, the structure of open flat hearths varies significantly. Some of this variation includes the presence or absence of perimeter stones. There are also differences in the thickness of ash, black and red layers within the structures, which may relate to duration of use, site organization,



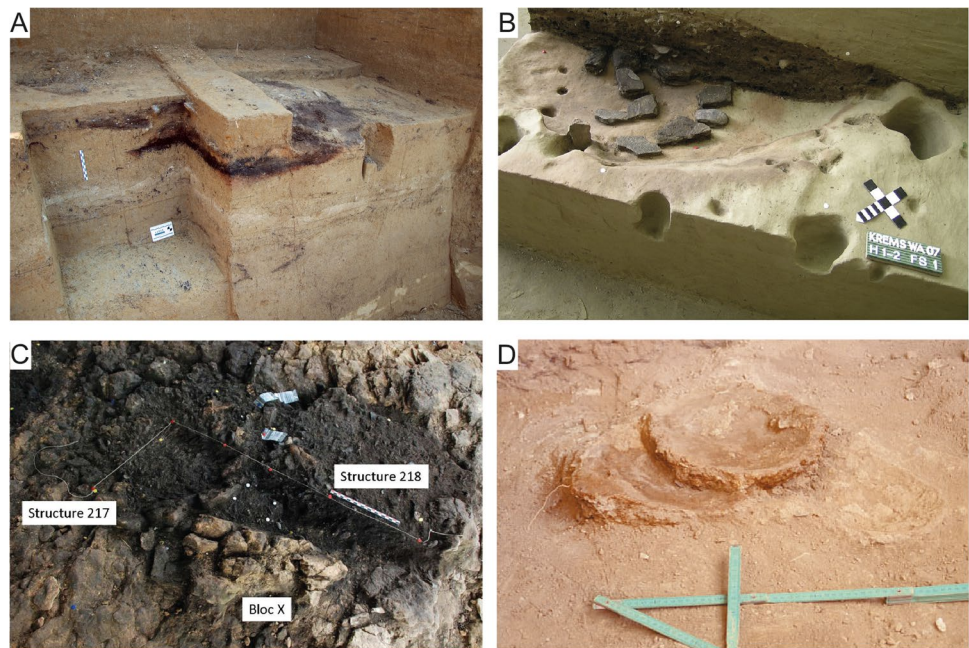
**Fig. 2** A) Map of all reviewed UP sites with described combustion features. Sites are categorized as 1 (blue), 2 (yellow) and 3 (purple) based on the published descriptive resolution available. Specific references for category 1 sites can be found in Table 1. Symbols indicate cultural associations. Numbers indicate the sites mentioned in this paper, further information can be found in the S.I.1. 115—Bacho Kiro, 126—Les Bossats, 129—Santa Maria d’Agnano, 130—Rio Secco, 133—Lagar Velho, 134—Vale Boi 135—Lapa do Picareiro, 136—Bistricioara-Lut’arie III, 137—Kostenki 14, 138—Šalitrena pečina, 140—Abrigo de La Boja, 150—Ratlla del Bubo, 151—Cova de Les Malladetes, 152—Korman 9, 153—Mezhyrich, 155—Verberie, 156—Pincevent, 157—Etiolles, 158—Hohle Fels, 159—Geißenklösterle, 160—Klisoura cave, 161—Theopetra, 162—Grotte di Fumane, 164—Cueva de Nerja. **B**) Map for southern France/Northwest Iberia, featuring all categories 2 and 3 sites reviewed. The numbers correspond to the following sites: 121—La Ferassie, 122—

Chez-Pinaud 2, 123—Abri Castanet, 124—Abri Cellier, 125—Abri Pataud, 142—El Parco, 143—Bauma de la Peixera d’Alfès, 144—Els Colls, 145, Can Garriga 1, 146—Moli de Salt, 147—Montlleó, 148—L’Hort de la Boquera, 149—Cova Gran de Santa Linya, 154—Régismont-le-Haut, 163—El Miron Cave. **C**) Map for the Middle Danube/ Moravia region of Central Europe featuring all Category 2 sites reviewed in the Middle Danube/ Moravia region of Central Europe. No category 3 data was available during our review in this area. This region includes sites in lower Austria, Czechia, Hungary, Poland and Slovakia. The numbers correspond to the following sites: 110—Galenburg-Stratzing, 111—Krems-Wachtberg, 112—Krems-Hundssteig, 113—Grub-Kranawetburg, 114—Grubgraben, 116—Dolní Věstonice I, 117—Pavlov 1, 118—Pavlov IV, 119—Dolní Věstonice II (a and 05), 120—Milovice IV, 128—Ságvár Lyukas Hill, 131—Henrykow 15, 132—Krakow Spadzista, 139—Cejkov 1

as well as site formation processes (Aldeias et al. 2016; Anderson et al. 2018; Leierer et al. 2019; Mallol et al. 2013b; Villaverde et al. 2021). At the Aurignacian open-air site of Régismont-le-Haut (France), 6 of the 31 combustion features were described as small flat peripheral hearths (Anderson et al. 2018; Lejay 2018). These structures vary between 90 and 25 cm in diameter and have limited thermal alteration of the underlying substrate, i.e. lack a well-developed red

layer (Anderson et al. 2018). Anderson and colleagues suggest these features were used ephemerally based on their thin red layers as well as being located away from the main areas of activity at the site (Anderson et al. 2018). While variation in dimensions and thickness of combustion can suggest intra-site organization, it can also indicate changes in mobility. The recent study of the combustion features at Grotte di Fumane showed a clear pattern of repeated short-term

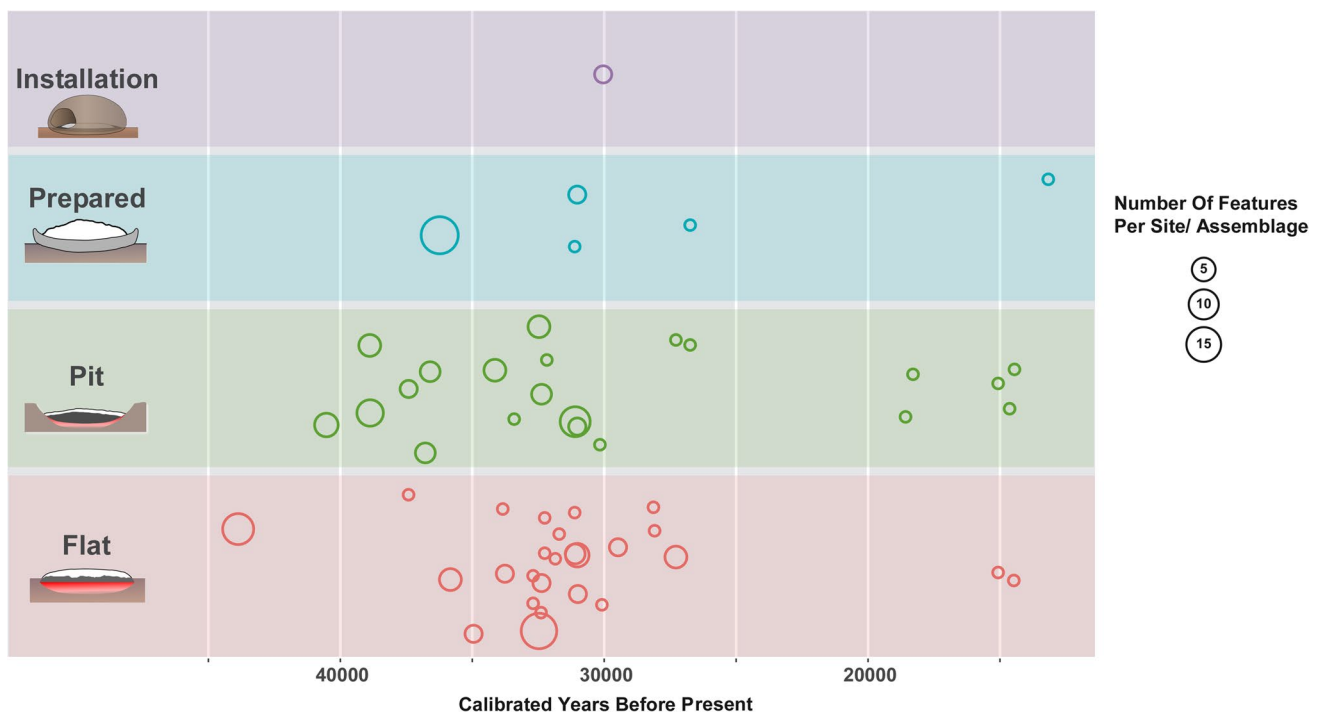
**Fig. 3** Examples of various types of Upper Palaeolithic combustion features: A) Unlined open flat hearth—Korman 9, Ukraine (Photo Credit: P.R Nigst, NEMO-ADAP Project), B Prepared Burning surface hearth with burned stone slabs at base (Hearth 1)—Krems-Wachberg, Austria (Simon et al. 2014), C) Pit hearth features during excavation of Abri Castanet. Note the bedrock to the sides and the darker infill of combustion-related sediment—Abri Castanet, France (White et al. 2017: Supplementary Fig. 7), D) Clay-lined prepared surface hearth—Klisoura Cave, Greece (Karkanis et al. 2004)



use by Neanderthals followed by a decrease in features associated with Uluzzian, followed by more organized and complex feature use in the Protoaurignacian (Marcazzan et al. 2022). This suggests AMH were occupying Grotte di Fumane for potentially longer periods of time compared to earlier Uluzzian and Neanderthal groups (Marcazzan et al. 2022). A similar pattern occurs at the Spanish site of Cova Malladetes, where flat hearths were described to increase in thickness and diameter between the different Aurignacian and Gravettian occupations (Villaverde et al. 2021). According to Villaverde et al. (2021), the increased diameter and thickness of combustion features associated with relatively richer archaeological assemblages in the late Aurignacian (level XII) through the Gravettian, particularly in the Gravettian layers IX and XI, suggests an intensification of site associated with longer duration of occupations. In comparison, the underlying Aurignacian levels XIII to XIVA have well-preserved successive hearths that are more short-lived in nature. Turning our attention towards eastern Europe, the excavations at the late Aurignacian site of Galenberg-Stratzing, in Austria, uncovered 17 combustion features and 8 charcoal concentrations found within two cultural layers (Neugebauer-Maresch 2008). Two of these features, hearths B and F, were lined hearths with complete stone circles, while another hearth, hearth C, had a partial circle of stones around it (Neugebauer-Maresch 2008). Hearth B was the most significant of the 17 combustion features due to its large size (1 m in diameter) and to the presence of a statuette found beside the structure (Neugebauer-Maresch 2008). Hearth B presented a 30 cm deep rubified (reddened) substrate, which suggests prolonged or intensive use of this feature (Neugebauer-Maresch 2008). The other combustion features

at this site were described as unlined flat hearths averaging 75 cm in diameter (Neugebauer-Maresch 2008). Concerning evidence associated with the Gravettian, at the open-air site of Les Bossats—Ormesson (France), recent excavation recovered evidence of two hearths in the Gravettian occupation layer. The first is a large oval-shaped hearth, while the second was a small circular hearth, 40 cm in diameter and surrounded by unheated stones (Lacarrière et al. 2015; Lejay 2018; Lejay et al. 2016). Meanwhile, unlined hearths were prominent within the Gravettian layers at Abri Pataud where Movius (Movius et al. 1977) described “bonfire”-type hearths such as in lens JI which had an area of 120–350 cm and a depth of 2–6 cm (Braadbaart et al. 2020; Movius et al. 1977). Lined flat hearths were also prominent at the Magdalenian sites of Balma de la Peixera and Els Colls in Spain (Fullola et al. 2012).

Another common characteristic of open flat hearths in the UP is the evidence of stacking within the same combustion loci. Stacking refers to the superposition of several discernible burning events which indicates to reuse of a combustion feature, presumably after a period of abandonment (Mallol et al. 2013a, b, 2017). Stacking is common characteristic of open flat hearths features found on Gravettian sites. Several of the flat combustion features from the Pavlovian hills sites of Pavlov I and Dolní Věstonice II were described as multi-layered, in which individual burning layers were separated by thin layers of loess (Beresford-Jones et al. 2011; Svoboda 2005). This includes hearths from Dolní Věstonice Iia and II-05. The hearth at Dolní Věstonice Iia consisted of a series of superimposed layers of dark charcoal-rich lenses measuring 110–120 cm in diameter and 25–30 cm thick (Beresford-Jones et al. 2011, 2010; Svoboda et al. 2015,



**Fig. 4** Temporal distribution of different contained combustion feature types per site and/ assemblage based on median calibrated years BP. Data was collected from individual combustion features described at Category 2 and 3 sites and was plotted using a jitter to avoid overplotting. Each bubble corresponds to the number of same

feature type for a given level at a site; therefore, a site with several feature types and/or features of different chronologies can be represented by more than one bubble. Dates were calibrated using OxCal 4.4 using the InCal20 calibration curve with a probability 95.4% (Bronk Ramsey 2009; Reimer et al. 2020)

2005). A similar hearth at Dolní Věstonice II-05 contained several charcoal lenses and rubified loess layers indicating hearth bases, which were separated by aeolian sediment (Beresford-Jones et al. 2011). At the nearby Gravettian site of Grub-Kranawetburg, Hearth I was interpreted as an open flat hearth roughly 90 cm in diameter and 10 cm in depth (Antl-Weiser 2008; Bosch et al. 2012). The analysis of Hearth I showed four different combustion layers/lenses, interpreted as four distinct phases of use, each separated by thin, 2 to 3 cm thick, layers of sterile loess (Antl-Weiser 2008). Another common characteristic at both Grub-Kranawetburg and the combustion structures at Dolní and Pavlov is the presence of small pits surrounding the main combustion features (Antl-Weiser 2008; Beresford-Jones et al. 2011; Svoboda 2005). At the Romanian EpiGravettian site of Bistricioara-Lut'arie III, a two phased hearth was described as having a high density of charcoal, calcined bone, ochre and burnt stone within the black layers (Anghelina et al. 2020a). At the Magdalenian site of El Parco, in Spain, excavators described over 40 different combustion features; several of which are flat hearths (averaging ~40 cm diameter) in levels II and III which vary between single and multiple uses, as well as other larger hearths (between 60 and 80 cm in diameter) that show evidence of intensive reuse and restructuring (Fullola et al. 2012).

Overall, these results show a large amount of variability in terms of structure and composition of open flat hearth features both from site to site and intra-site. However, based on the available evidence, we assume open flat hearths are underrepresented in our review. Several sites that we reviewed, and ranked as category 1, mention evidence of burning or the presence of hearths but lack references or available descriptions of the combustion features for our analysis and classification. We assume many of these structures are open flat hearths, but these hearths have not been included within our analysis due to the lack of available descriptions.

**Pit structures** The second prominent type of contained combustion features in the UP are pit structures. Pit structures are combustion features placed within an intentionally dug depression in which the surrounding substrate is used to both contain and control combustion in reducing conditions (Mallol et al. 2017). Our review identified several examples throughout the UP. Several of the structures associated with the early UP and Aurignacian technocomplex are clustered within southern France and on the Iberian Peninsula. The majority coming from cave sites in the Périgord region of France like Abri Pataud, Abri Castanet, Abri Blanchard and Abri Cellier (Braadbaart et al. 2020; Movius et al. 1977;

White et al. 2017). Structurally, the pit features from Abri Castanet, Blanchard and Cellier are similar in their construction and form, many of which were dug directly into the limestone bedrock of the caves (White et al. 2017). The pit features from Abri Castanet consists of three separate pits in close proximity to one another (White et al. 2017). One of the three structures (structure 217) has been interpreted as a primary burning structure while the other two features (structures 216 and 218) were interpreted by White et al. (2017) as used to either control heat or dump ashes from the primary combustion feature of structure 217. Similar arranged structures were found at the nearby sites of Abri Cellier and Abri Blanchard (White et al. 2017). However, at these sites further research into the nature and contents of the features was not possible as most of the sediments had been removed by previous excavations (White et al. 2017). At Abri Pataud (France), pit hearth features are found throughout the Aurignacian and Gravettian levels (Braadbaart et al. 2020; Movius et al. 1977). The pits are described as basin-like whose depth (5–20 cm) and dimensions vary significantly, many of which are filled with burned bone, ash and fire cracked stones (Braadbaart et al. 2020; Movius et al. 1977; Théry-Parisot 2002). Several of the hearths in the early Aurignacian levels of Abri Pataud, like at Abri Castanet, were dug directly into the limestone bedrock. Outside of the Périgord region, pit features were also found in the EUP and Gravettian Levels at the Spanish site of Cova Grande Santa Linya (Martinez-Moreno et al. 2010; Sánchez-Martínez et al. 2020). These pit features were described as small hearths, 50 cm in diameter (Martinez-Moreno et al. 2010; Sánchez-Martínez et al. 2020). Pit features were also found at the French site of Regismont-le-Haut, with 7 of the 31 combustion features excavated described as roughly circular in shape lying within shallow depressions (~5 cm in depth) (Anderson et al. 2018; Lejay 2018). Two potential Aurignacian hearths were described as being dug into the underlying substrate at the Serbian site of Šalitrena pećina (Plavšić et al. 2020).

In the MUP and LUP, the evidence we identified in our review suggest that pit features become a much more widespread phenomenon. At the Gravettian site of Lagar Velho (Portugal), one of the combustion features was within an artificial depression ~20 to 25 cm in depth (Almeida et al. 2009). Several of the pit features from Dolní Věstonice I were described as kettle- or bowl-shaped pits, ranging between roughly 1 to 2 m in diameter and 50 cm to 1 m in depth (Svoboda et al. 2018, 2005). However, at Dolní Věstonice I many of the structures appear to be within stretched lenses of sediment, which may indicate post-depositional disturbances and alteration of the combustion features present at the site (Verpoorte 2000). Similar features were described at the nearby sites of Pavlov I, Dolní Věstonice II and Předmostí (Beresford-Jones et al. 2010;

Svoboda 2005, 2013, 2007; Svoboda et al. 2013, 2016). At the Epi-Gravettian site of Mezhyrich, Ukraine, a circular pit feature was described as 50 cm in diameter, 20 cm in depth and filled with ash and charcoal (Marquer et al. 2012; Soffer et al. 1997). Like other Gravettian open flat hearths described above, several of these structures were surrounded by secondary pit features, usually found in a semicircular arrangement (Antl-Weiser 2008; Svoboda 2005; Svoboda et al. 2018).

Our results indicate pit structures vary in depth as well as in construction. Two well-structured stone filled pit hearths were described with the Solutrean-Gravettian layers (OH 5 and 6) at the Abrigo de la Boja, Spain (Badal et al. 2019). Another example comes from the Magdalenian site of La Cova de les Cendres in Spain, where Hearth b14 was described as a cuvette hearth, 10 cm deep surrounded by stones (Bergadà et al. 2013; Villaverde et al. 2019). Similar cuvette hearths were found at the open-air Magdalenian sites of Verberie and Etiolles in France (Wattez 1994) (Wattez 1994). Hearth S29 at Etiolles was described by Wattez (1994) as a bowl-shaped structure filled with a mixture of bone, charcoals and ash. A similar feature (M20) at Verberie was described by Wattez (1994) as a cuvette hearth filled with burned limestone, burned bone and burnt flint (Wattez 1994). Based on the low proportion of combustion materials within the thin sections from both hearths, Wattez (1994) concluded that each of the hearths was used on a short-term, low-intensity basis (Wattez 1994). Another prominent multi-layered pit structure was described at the Magdalenian site of El Miron in Spain (Nakazawa et al. 2009; Straus et al. 2013). The combustion feature at El Miron was 140 cm in diameter and 20 cm deep with four distinct burning events (Nakazawa et al. 2009).

**Prepared burning surfaces** The third type of contained combustion features are prepared burning surfaces. Prepared burning surfaces are hearths built over anthropogenically modified substrates, such as on stone or clay linings (Mallol et al. 2017). The only clear evidence of prepared burning surfaces prior to the Gravettian were found within the Aurignacian levels of Klisoura Cave, in Greece (Karkanas et al. 2004; Koumouzelis et al. 2001). Of the 90 combustion features from Klisoura cave, 54 were described as clay-lined basin-like structures sunk into the ground (Karkanas et al. 2004; Koumouzelis et al. 2001). The clay-lined basins are ~30–40 cm in diameter and vary between 10 and 20 cm in depth (Karkanas et al. 2004; Koumouzelis et al. 2001). Micromorphological analysis of several of the combustion structures indicated that the clays used for the basin lining were brought in from outside of the cave. In addition, several of the combustion structures were interstratified meaning they were either built on top of or intersect with one another (Koumouzelis et al. 2001).

Like the evidence for pit structures, the presence of prepared burning surfaces are more widespread in the MUP and Late UP. In the Gravettian, there are several examples from the Middle Danube region of Europe. At the site of Krems-Wachtberg in Austria, hearth 1 was described as a complex multiphase combustion feature within a shallow depression (Simon et al. 2014). Hearth 1 had three clear phases of utilization with burned stone slabs making up the base of the hearth as well as a second layer of burned stone between the first and second phases of use (Simon et al. 2014). The excavators also uncovered at least 10 associated features, 5–10 cm in diameter and 10–25 cm in depth grouped around Hearth 1; the grouping of which is similar to other Gravettian sites in the region (Händel et al. 2014, 2015; Simon et al. 2014). Another example of prepared burning surfaces is from the nearby Gravettian site of Pavlov I. Here, Hearth H33 was described as a circular structure with limestone blocks at its margins (Svoboda 2005). The base of hearth H33 was covered in heavily fire damaged flat sandstone tablets (Svoboda 2005). Another feature, hearth H23, also had a layer of burnt limestone blocks at the base (Svoboda 2005). Like Hearth 1 at Krems-Wachtberg and other Gravettian sites in the region, H23 was also surrounded by kettle-shaped pits filled with ash mixed with bone and lithics (Svoboda 2005). Similar potential prepared burning surfaces were described at the nearby site of Dolní Věstonice II (Svoboda et al. 2015; Svoboda 2016). While limited in detail, several hearths at Dolní Věstonice II were described as complex features filled with limestone fragments; however, it is unclear whether these limestone blocks were incorporated into the structure as a burning basal surface or had another use (Svoboda 2016). The ongoing excavations at Bistricioara-Lut̃arie III in the Eastern Carpathian mountains uncovered another potential stone-lined base of a hearth associated with the Late Gravettian layer 2.4 (Anghelinu et al. 2020a).

In the late UP, there are examples of prepared surface hearths found on Iberian Solutrean and Magdalenian sites. A hearth from the Solutrean-Gravettian level SW18B1 of Abrigo de La Boja (Spain) was described as a basin hearth, 1 m in diameter and 10 cm deep, with fire cracked rocks covering a rubified base (Lucena et al. 2013). A similar feature was described at the Spanish Solutrean-Gravettian site of Ratilla del Bubo, in which a large hearth, 62 cm in diameter, has a central burned stone at its base and was lined with stone around its perimeter (Fullola et al. 2012). Another large Magdalenian potential prepared burning surface was excavated within layer F from Lapa de Picareiro in central Portugal (Belmiro et al. 2020; Benedetti et al. 2019; Bicho et al. 2006). The hearth was described as a large, prepared basin, 2.5 m in diameter and 40 cm deep, in which the exterior and base of the hearth were lined with limestone slabs (Bicho et al. 2006). A clay-lined hearth was also described at the Spanish Magdalenian site of Moli de Salt (Fullola et al.

2012). At the Epi-Gravettian site of Grubgraben, Hearth 1 was described as a stone-lined hearth, 50 cm in diameter, with several thin heat-altered stone slabs at the base of the structure (Einwögerer 2021).

**Fire installations** The fourth type of contained combustion features, fire installations, are exceptionally rare as well as exceedingly difficult to identify in the UP. Fire installations are human-made containers consisting of a prepared substrate as well as walls and a roof to contain and control heat (Mallol et al. 2017). The only two potential examples of these types of combustion features are two “kiln-like” hearths from Dolní Věstonice I (Svoboda et al. 2015, 2018; Vandiver et al. 1989). The two structures, found within residential units K2 and K3, were excavated by B. Klima in the 1950–1970s (Svoboda et al. 2018). The combustion feature within K2 was described as a hollowed out hearth measuring 130 by 40 cm and 40 cm deep, surrounded on three sides by burned red loess which was originally interpreted by Klima as part of a collapsed vaulted roof (Svoboda et al. 2018; Vandiver et al. 1989). The second feature within unit K3 was described as a pan-shaped pit, 1 m in diameter and 60 cm deep; the base of which was lined by clay mixed with rubble (Svoboda et al. 2018). This combustion feature was filled with partially burned mammoth bones (Svoboda et al. 2018). Two narrow grooves or channels were discovered running from the features entrance which were interpreted by Klima as air ducts (Svoboda et al. 2018). Both hearths have substantial amounts of baked clay ceramic materials found within the hearth fill and were originally interpreted as kiln-like ovens (Svoboda et al. 2018; Vandiver et al. 1989; Verpoorte 2000). However, there is considerable debate over whether these structures were ovens or the result of complex site formation processes (Svoboda et al. 2018; Verpoorte 2000). The Upper Section of Dolní Věstonice I shows evidence of solifluction, which could have altered and modified the sediments in and around the hearths (Svoboda et al. 2018; Verpoorte 2000). Due to the early dates of these excavations and lack of remaining materials from the hearth areas it is not possible to determine either way (Svoboda et al. 2018).

**Other evidence of fire use in the UP** Finally, we were also able to collect limited data on uncontained anthropogenic combustion features including ash dumps and hearth maintenance behaviours. Three prominent examples of which include Aurignacian and Gravettian layers from Hohles Fels and Geißenklösterle (Miller 2015; Schiegl et al. 2003) and from Aurignacian site of Regismont-le-Haut (Anderson et al. 2018). At both Hohles Fels and Geißenklösterle (Germany), there were no clear evidence of in situ combustion features within the Aurignacian and Gravettian assemblages. However, there was clear evidence of burned materials

including charcoals, burned bones, ash and burned limestone fragments (Miller 2015; Schiegl et al. 2003). Micro-morphological investigations at both sites lead to the interpretation that these layers of burned material were the result of dumping zones of combustion residues for hearth maintenance activities (Miller 2015; Schiegl et al. 2003). Similar hearth maintenance features were found near the periphery of the main occupation areas of Regismont-le-Haut where excavators described patches of ashy or charcoal-rich sediments (Anderson et al. 2018; Lejay 2018). While outside of the scope of sedimentary artefacts, it is also interesting to note on the presence of portable light sources at Cueva Nerja (Spain) associated with the Solutrean, which, for now, remain rare types of fire-associated artefacts during the UP (Medina-Alcaide et al. 2019, 2021, 2015).

## Discussion

Overall, our review shows a complex pattern for evolution of pyrotechnology throughout the UP of Europe. Chronologically, our results show an increasing complexity, intensity and widespread use of various forms of combustion features from the IUP to the MUP. While well-documented examples of hearths are rare in association with IUP assemblages, our results suggest the use of open flat hearths during this period. None of the IUP combustion structures we reviewed appeared to have perimeter stones and there is little evidence of stacking, reuse or hearth maintenance behaviours (see Marcazzan et al. 2022 with the possible exception in the Protoaurignacian of Grotte di Fumane). If this evidence holds once more sites are studied, this may suggest that IUP combustion features were only used ephemerally with little investment in the long-term use and maintenance of combustion features.

In contrast, the evidence for pyrotechnology in the EUP appears to be more diverse, albeit geographically clustered. The two major clusters of complex combustion features suggest a regionalization of pyrotechnology in the EUP, with pit features developing in western Europe and prepared burning surfaces developing in the eastern portion of Europe. While the clustering of our results likely reflects clear biases in terms of preservation and greater availability of data from these regions compared to other parts of Europe; it also could represent a unique developmental period of pyrotechnological convergence in which different populations independently develop “signature” forms of pyrotechnology in what, for now, appear to be restricted regional contexts. The driving force for this potential regionalization of pyrotechnology is currently unclear as this pattern needs to be more thoroughly explored in future research paragraph. Apart from the potential regionalized development of pyrotechnology, evidence for fire use in the EUP can still be characterized as low intensity and ephemeral. While there is evidence

of hearth maintenance behaviours at Aurignacian sites like Regismont-le-Haut, Hohles Fels and Geißenklösterle, most EUP sites we reviewed either lack this type of behaviour or are under reported/studied. Moreover, evidence of stacking and reuse of EUP hearths are exceedingly rare. Overall, very few EUP sites show evidence of intensive occupations, especially in Central and Eastern Europe (Hauck et al. 2018).

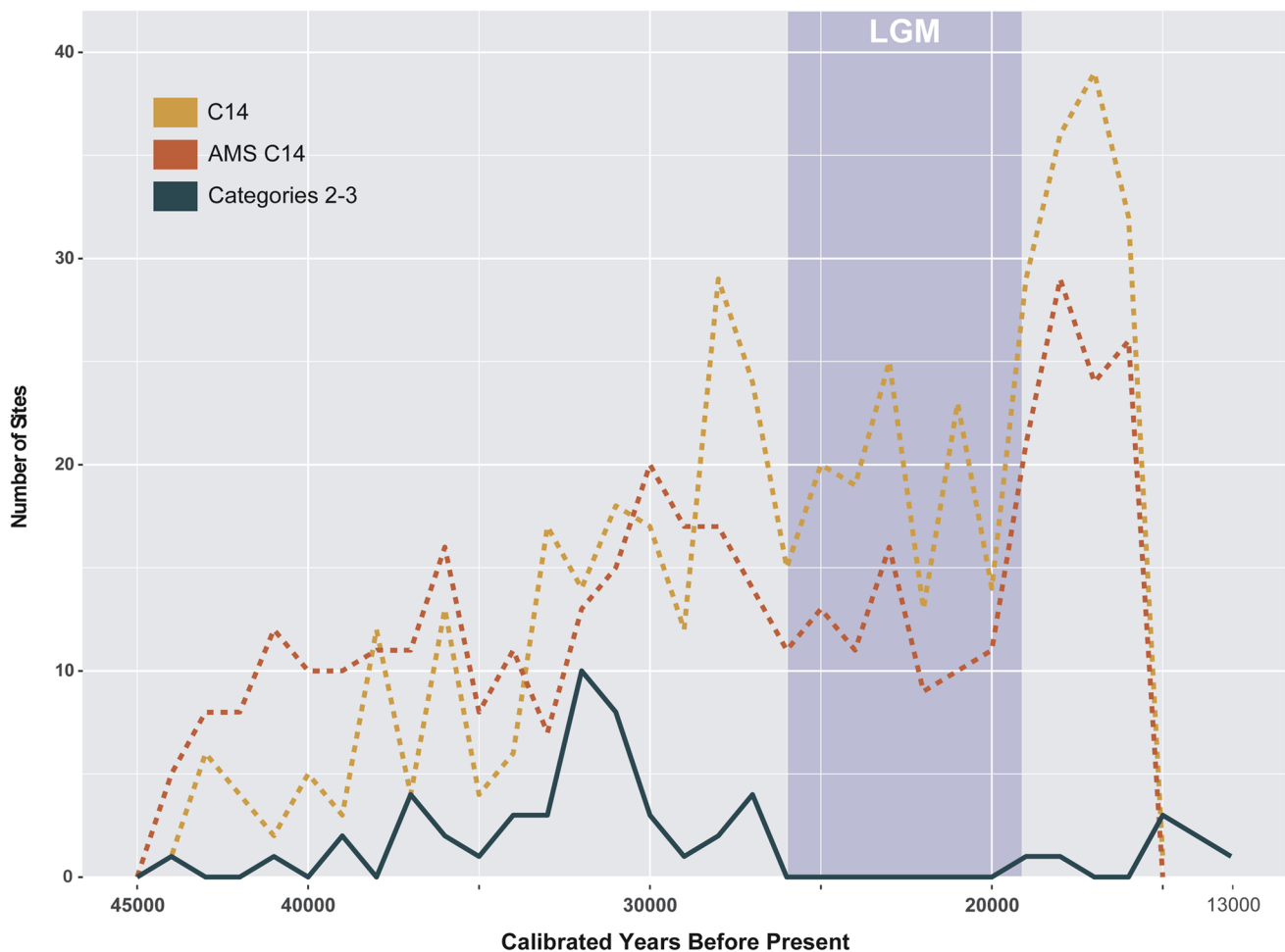
Our analysis suggests that a major shift in the use of pyrotechnology takes place between 36 and 28 ka cal BP. The evidence for pyrotechnology associated with the Gravettian, 32–28 ka cal BP, reflects a staggering change in the intensity of use, form and function of modern human fire use compared to early periods in the UP. The reviewed evidence suggests that Gravettian populations were not only using a broad range of combustion feature types—including the first evidence of potential fire installations—but their use was spread over a much wider scale in comparison with the early UP (Fig. 2). In addition to widespread use of complex combustion features, the evidence for baked clay and loess objects from several Gravettian sites in the Middle Danube region (Antl-Weiser 2008; Farbstein and Davies 2017; Simon et al. 2014; Svoboda et al. 2015; Vandiver et al. 1989; Verpoorte 2000; Vlačičky et al. 2013) represent a departure from previous pyrotechnology with the emergence of baked andromorphic figure clays associated with combustion features. This evidence suggests a different use and conceptualization of fire with the manufacture of non-utilitarian items. While it is clear that both Neanderthals and AMH used fire for a variety of different reasons beyond lighting, warmth and cooking prior to the Gravettian, such as the production of adhesives and treatment of raw materials (Mallol and Henry 2017; Mallol et al. 2019a, 2013a; White et al. 2017), the creation of cultural, potentially symbolic items, as the anthropomorphic figurines represents a major behavioural shift in modern humans (Vandiver et al. 1989).

Changes in fire use in the MUP is also expressed by the evidence of extensive structural complexity and intensive reuse of combustion features over long periods of time (Antl-Weiser 2008; Bosch et al. 2012; Händel et al. 2014, 2015; Pryor et al. 2016; Simon et al. 2014; Svoboda et al. 2011, 2015). Our results show many Gravettian hearths surrounded by circular or semicircular arrangement of secondary features which have various functional interpretations, including fuel storage, boiling pits for grease production, as well as waste removal and heat control (Bosch et al. 2012; Fladerer et al. 2014; Simon et al. 2014; Svoboda et al. 2015, 2016, 2018; Svoboda 2016). While the exact function of these auxiliary structures can be debated, as it can their contemporaneity, their presence still implies an extensive investment in time and resources by modern human populations into making these structures as well as in site organization and resource management. Several papers, such as Pryor et al. (Pryor et al. 2016), suggest Gravettian populations were

semi-sedentary, which is based on the substantial evidence of long-term occupations at several Gravettian sites across central Europe. While it is difficult to determine the passage of time between reuses of a combustion feature (Mallol et al. 2013a), several Gravettian fire features, like those at Krems-Wachtberg and Grub-Kranawetburg, show successive layers of repeated use and abandonment of the same heating loci (Antl-Weiser 2008; Bosch et al. 2012; Händel et al. 2014, 2015; Simon et al. 2014). This evidence implies that Gravettian groups are not only reusing the same open-air sites and structures repeatedly, but also suggests they had advanced knowledge of existing fuel resources nearby and the location of previously used combustion features, which might not be so obvious at an open-air site when compared to a more constrained habitat, such as a cave site (Pryor et al. 2016). This change in mobility and site occupation patterns has broader implications in terms of how Gravettian populations

selected site locations and approached problems such as the long-term availability of fuel resources (Pryor et al. 2016). Overall, variations in Gravettian pyrotechnology reflects a wider cultural and technological changes taking place in modern human behaviour in the MUP.

Surprisingly, however, our results show a clear gap of well-described combustion features during the height of the LGM between 26 and 19 ka BP. Figure 5 shows the chronological distribution of our categories 2 and 3 data in comparison with UP sites with available radiometric and AMS C14 data within the Radiocarbon Palaeolithic Europe database V28 (Vermeersch 2020). As this figure illustrates, while there is a decline in sites within the Radiocarbon database between ~28 and 19 ka cal BP, there are still substantially more UP sites during this period than the EUP between 48 and 35 ka cal BP. Therefore, a lack of sites cannot be used to effectively explain the lack of well-described combustion



**Fig. 5** Comparison between the availability Category 2 and 3 site data compared to sites with C14 and AMS C14 dates within the Radiocarbon Palaeolithic Europe Database V28 (Vermeersch 2020). The rectangle indicates the height of the Last Glacial Maximum (LGM)

26–19 ka BP. The median dates for Categories 2–3 were calibrated using OxCal 4.4 using the InCal 20 calibration curve with a 95.4% probability (Bronk Ramsey 2009; Reimer et al. 2020)

features during the LGM. Based on this analysis, we suggest three potential explanations for the lack of available data in the LGM. The first, and most parsimonious answer, is that this lack of well-described combustion features is a result of the limited availability of usable datasets. As we have shown throughout our review, the reported evidence for UP fire use is inconsistent and patchy; therefore, the lack of evidence during the LGM likely reflects a poor publication history of combustion features, which is indeed common throughout the UP archaeological record. The second explanation for the lack of published datasets could be the poor preservation of combustion features during the LGM. This period is marked by extreme cold and rapidly changing environmental conditions (Anghelinu et al. 2020b; Banks et al. 2008). While several experiments have shown the effects of freeze–thaw-related processes and periglacial conditions on other types of material culture (Lenoble et al. 2008; Texier et al. 1998), we still lack more in-depth studies into the effects of cryoturbation on combustion features and associated sediments (Masson 2010). The third possible explanation into the lack of well-described combustion features in the LGM could be that simply there is no fire present at many sites. While AMH could use fire habitually, the use of fire in many of these sites was likely limited by the availability of fuel sources. The lack of fuel, or the high costs of fuel collection, could have been particularly relevant in northern latitudes where tree cover was more strongly impacted by extreme cold environments (Henry 2017; Pryor et al. 2016). LGM occupation sites with no evidence of fire use, i.e. with a demonstrated absence of combustion features or residues, could suggest different human groups had other behavioural Adaptions to surviving in extreme conditions apart from fire use (Speth 2017). In this regard, it might be noted that the absence of combustion features during glacial periods has also been proposed for several Neanderthal occupations at sites in the southwest France (Dibble et al. 2018). However, it is extremely difficult to evaluate the absence of fire based on publications alone, as such we are merely noting the possibility that some AMH groups did not use or have access to fire during the LGM as a possible explanation for the lack of well-described features during this period. None of the three explanations we have proposed above are meant to be mutually exclusive and it is entirely possible that the lack of data from the LGM is a combination of any of the three. For now, the lack of available experimental and archaeological datasets prevents us from fully understanding the effect that the LGM cold conditions had on modern human fire use.

What is clear is that towards the end of the LGM (19–13 ka BP), we have the re-emergence of well-described fire features in the UP record. Late UP combustion features follow a similar regionalized distribution pattern as main technocomplexes found at the end of the LGM. Most of the well-described evidence associated with the Magdalenian

and Solutrean technocomplexes come from southern France and Iberia. As in the MUP, several of the well-described Magdalenian combustion features can be classified as pit structures and prepared burning surfaces with evidence of intensive reuse and the presence of perimeter linings (Bergadà et al. 2013; Fullola et al. 2012; Nakazawa et al. 2009; Villaverde Bonilla 1985). However, evidence from sites like the Magdalenian site of El Parco, in Spain, while not as well described, shows a predominance of open flat hearths throughout multiple layers (Fullola et al. 2012). Similar preference for open flat hearths is apparent at several of the Solutrean and Magdalenian sites like Ratlla del Bubo and L'Hort de la Boquera in Spain, which show intense reuse and restructuring of flat lined hearth structures (Fullola et al. 2012). Meanwhile in Central and Eastern Europe, the limited EpiGravettian record suggests a similar complexity of fire use to the earlier MUP. The EpiGravettian sites of Mezhyrich and Korman 9, in Ukraine, suggest a preference for open flat hearths along with limited evidence of pit features (Kulakovska et al. 2021; Marquer et al. 2015, 2012; Кулаковська et al. 2019). While evidence of combustion features at the ongoing excavations at Grubgraben suggest the use of complex prepared surface structures (Einwögerer 2021). Overall, the evidence collected during our review suggest that open flat hearths dominate the late and post-LGM landscape. However, it is currently unclear whether use of these types of structures are the result of expedience, resource stress or reflect the changing needs of AMH living within the late LGM landscape.

Additionally, we tested our data to examine the influence of site setting, i.e. cave sites vs open-air sites, on the temporal and regional patterns of fire use in the UP. As we have only a limited dataset, and we can only consider the effects of post-depositional processes on a site-by-site basis when/where it has been reported, it is difficult to determine whether the site setting influences temporal or regional patterns. As stated in the section above, our data suggest there is potential regionalization of pyrotechnology during the EUP. However, this pattern is isolated to cave sites in Greece and southwest France, with the exception of the combustion features from the open-air site of Regismont-le-Haut (Anderson et al. 2018). The evidence from other Aurignacian open-air sites we reviewed is much more limited but appears to lack the structural complexity of the cave sites from these regions. This pattern likely could represent a publication or preservation bias for this time period. Meanwhile our results for the MUP and LUP suggest site setting had a negligible influence on the types of combustion features present as similar types of features are found in both cave and open-air settings. We believe the publication of data in the future could potentially shed a light on these potential patterns that we otherwise are unable to fully test with the currently available data.

**Bias in published data and the need to standardize archaeological observations** Throughout our review of available datasets, our results suggest there is a potential for interpretational bias in terms of the reporting and identification of both pit and prepared surface structures. Overall, the descriptions of UP combustion features are inconsistent and patchy. While we have identified several well-described pit and prepared burning surface features, it is very likely that these types of structures are overrepresented within the available literature when compared to open flat hearths. Independently, however, the available pit feature descriptions and dimensions vary significantly in the UP, and while it is clear these features were found in depressions, in some cases it is unclear whether these are naturally occurring or anthropogenically dug features (Leierer et al. 2020). The recent study on Middle Palaeolithic pit features by Leierer et al. (Leierer et al. 2020) points out many of the difficulties of identifying pit features directly in the field. Multiple experimental studies using fire on flat surfaces have shown that prolonged exposure to heat thermally alters the underlying substrate (Aldeias et al. 2016; Mallol et al. 2013a; March et al. 2012). In many cases, this thermal alteration can be spherical in appearance (Aldeias et al. 2016). The lack of descriptions of thermally altered substrates at many sites means there is potential for misidentification of pit features using macroscopic field observations.

There are similar issues identifying prepared surface features within the literature as well. While combustion features at several sites are described as having burned stones within the hearth matrix (e.g. Movius Jr 1966), it is not clear when these stones were added to the combustion feature; whether prior to firing or when the feature was already in use; or even whether the presence of stones in the combustion materials is intentional or result of input from the surrounding matrix. As, by definition, a prepared burning surface is a purposely built structure, preconstructed artificial substrate on which combustion takes place, we were unable to make a definitive classification of several hearths described in the literature. In many older excavations and publications separating objective quantitative data from interpretation is difficult and while this data is still invaluable on an individual site basis—and was excellent for the standards of their time—we need modern objective datasets to make effective comparisons and classifications.

Our capacity to better understand the evolution of Pyrotechnology and better test the emerging patterns highlighted in this review, is, however, hampered by a lack of in-depth analysis of fire features and standardization of the way we report such features—this is unfortunately true even in modern excavations. Examples of what parameters should be recorded and described for field excavations of fire remains have been proposed (e.g. Mallol and Henry 2017)—see also the recorded variables used for this paper and detailed in the

SI. A more widespread application of both standardized field and laboratory methods to study fire features, as well as their more systematic publication by archaeologists, will greatly improve our understanding of fire use in the human past. We hope that, by reviewing available data, we have highlighted the value of pyrotechnology to track past behaviours and the need for reporting on fire evidence also in periods for which we already assume fire was controlled and habitually used.

## Conclusion

While much research has focused on when humans started to use fire and there has been a recent effort in understanding fire among Neanderthals, far less is actually known on UP fire use by AMH. To fill this gap, here we have reviewed the evidence for pyrotechnology in association with UP techno-complexes to better characterize the use of fire and how such use changed among AMH in Europe. We collected data from published macro-observations and, when available, micro-stratigraphic and site formation data on combustion features, including dimensions, presence, thickness and nature of ash, charcoal, burned artefacts, black layers and heat-altered substrates layers. To systematize the available evidence, we have adapted and applied a classification system proposed by Mallol et al (2017) to describe contained combustion features as seen in the field.

The results show emerging temporal distinctions, for instance, with geographical clustering that may reflect regionalization of pyrotechnological traditions during the Aurignacian, whereas there is an extensive structural complexity and intensive reuse of combustion features during the Gravettian. Interestingly, our results show a gap in well-described combustion features during the height of the LGM between 26 and 18 ka BP, though sites from these chronologies do exist in Europe. This observation may be due to lack of reporting, lack of preservation or, alternatively, due to lack of fuel for extensive fire use during this cold period. Indeed, more in-depth studies, experimental work and systematic reporting are needed to fully understand this and other trends suggested when we take a broad view of the available data. For instance, the presence of more complex features, such as pit or structured hearths, might be considerably overrepresented in published datasets when compared to—perceptibly—simpler open flat hearths.

Overall, this review has highlighted the requirement for greater standardization and more in-depth reporting of combustion features in published literature. The results and observations presented here likely represent an only limited view in the wider use and evolution of pyrotechnology in the UP of Europe. It is our expectation that the

emerging patterns discernible with the available data will be further tested with future increase of publications related to UP pyrotechnology. While we highlight the need for more micromorphological and geochemical analysis of combustion features, we should highlight that most of our results and observations were based on published detailed field descriptions. The data collection criteria we propose within our methods (see also the SI), represents one possible means of standardization for reporting combustion feature in the literature. It is only through the publication of more detailed descriptions and analysis of combustion features in the UP that we can better understand the development of modern human fire use and how it fits into our evolutionary model for how pyrotechnology developed in hominin evolution.

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## Declarations

**Conflict of interest** This research did not involve human participants and/or animals and there is no potential conflict of interest.

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