

William Chase Murphree

**Upper Palaeolithic pyrotechnology and its preservation in periglacial
environments**

**Pirotecnia do Paleolítico Superior e sua preservação em ambientes
periglaciares**



Universidade do Algarve
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William Chase Murphree

Upper Palaeolithic pyrotechnology and its preservation in periglacial environments

Doctoral dissertation in Archaeology

Supervisor:

Dr Vera Lúcia Dias Aldeias



Universidade do Algarve
Faculdade das Ciências Humanas e Sociais

2024

Authorship declaration

Upper Palaeolithic pyrotechnology and its preservation in periglacial environments

I declare to be the author of this work which is original and unpublished. Authors and works consulted are duly cited in text and listed in the reference list included.

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Dedication

This thesis is dedicated to my grandmothers: Delores Ann Ponte and Ramona Annette Wall Murphree. I miss you both.

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Abstract

The use of fire as a tool, or Pyrotechnology, is widely considered to be a pivotal technological innovation in hominin evolution and a hallmark of the genus *Homo*. While the research interest in the evolution of pyrotechnology has dramatically increased over the last few decades, the field has been primarily focused on the understanding the so called “origins” of fire use in hominin behaviour and using assumptions made regarding the “ubiquitous” use of fire by modern humans for comparisons with earlier periods. Currently, we know more about fire use during the middle Pleistocene than we do about the development of pyrotechnology in the last 50,000 years.

This PhD thesis is focused on the evolution of pyrotechnology during the Upper Palaeolithic of Europe (~50,000 – 13,000 years before present) and how the evidence of fire is preserved in periglacial conditions, where cryogenic processes can affect the integrity of combustion remains. Research was carried out via a comprehensive review of the combustion features throughout the Upper Palaeolithic in Europe, a case study with one of the first high resolution detailed analysis of combustion features used during the Last Glacial Maximum, and the development of an experimental protocol to characterize the effects of freeze-thaw processes on combustion remains.

The results show the evolution of pyrotechnology in the Upper Palaeolithic, with striking patterns of regionalisation and increased functional standardisation, as well as gaps on fire evidence during glacial periods. The study case and experimental work suggested that a lack of preservation may not be the most parsimonious reason for the gaps during glacial periods. Taken together, this evidence has led me to suggest that fire use might not have been as universally used, especially within times and/or regions of

limited available resources. This thesis highlights importance of studying pyrotechnological evolution to reconstruct past human behaviour and adaptation.

Keywords: Pyrotechnology, Upper Palaeolithic, Geoarchaeology, Micromorphology, Experimental Archaeology, Periglacial Environments

Resumo

A utilização do fogo enquanto ferramenta, ou seja, a pirotecnologia, é considerada como uma das inovações tecnológicas mais cruciais na evolução dos hominíneos, bem como um marco distintivo do gênero *Homo*. Embora os estudos científicos sobre a evolução da pirotecnologia tenham aumentado significativamente nas últimas décadas, a investigação tem se concentrado principalmente na compreensão das chamadas "origens" do uso do fogo no comportamento dos hominíneos, utilizando suposições feitas sobre a ubiquidade do fogo por parte dos humanos modernos durante o Paleolítico Superior para efetuar comparações com períodos anteriores. Desta forma, atualmente, sabemos mais sobre o uso do fogo durante o Pleistoceno Médio do que sobre o desenvolvimento da pirotecnologia nos últimos 50 000 anos.

Esta tese de doutoramento concentra-se no estudo da evolução da pirotecnologia durante o Paleolítico Superior na Europa (~50 000–13 000 anos antes do presente), focando-se também em como as evidências do fogo são preservadas em condições periglaciais, onde os processos criogênicos podem afetar a integridade dos vestígios de combustão. Estes trabalhos englobam as seguintes facetas: uma pesquisa exaustiva, por meio de uma revisão abrangente, das estruturas de combustão existentes ao longo do Paleolítico Superior na Europa (Capítulo 3); a aplicação de metodologias geoarqueológicas num caso de estudo com uma das primeiras análises de alta resolução de estruturas de combustão utilizadas durante o Último Máximo Glacial (Capítulo 4); bem como o desenvolvimento de um protocolo experimental para caracterizar os efeitos dos processos de gelo-degelo (crioturbação) na preservação de vestígios de combustão (Capítulo 5).

Adicionalmente, o capítulo 2 apresenta uma avaliação crítica do atual quadro teórico para o estudo da evolução do uso do fogo no Paleolítico. Neste capítulo, abordo alguns dos problemas da pesquisa atual sobre pirotecnologia, como a dependência excessiva de suposições generalizadas sobre o uso do fogo e a possível sobrestimação da prevalência desse uso no registo Pleistocénico. Também examino os custos associados ao uso do fogo e alguns dos pressupostos assumidos sobre o registo da pirotecnologia durante o Paleolítico Superior. Por fim, destaco as metodologias e o enquadramento geoarqueológico utilizados ao longo desta tese.

O Capítulo 3 faz parte de uma revisão bibliográfica publicada em 2022. Neste artigo, reuni metadados de descrições publicadas de estruturas de combustão, nos quais identificamos padrões notáveis de regionalização delareiras, bem como o aumento da padronização funcional perceptível durante as fases de início e meio do Paleolítico Superior. Este trabalho evidencia também a presença de lacunas nas evidências de uso do fogo durante o Último Máximo Glacial. Perante estes resultados, sugerimos três explicações possíveis para essas lacunas, nomeadamente: 1) uma ausência de publicações acessíveis, 2) um efeito de fraca preservação dos vestígios associados com climas frios e processos peri-glaciares, e/ou 3) uma efetiva ausência de uso do fogo durante períodos de frio extremo.

O Capítulo 4 é um estudo de caso sobre estruturas de combustão utilizadas durante o auge do Último Máximo Glacial no sítio ucraniano de Korman'9. Este capítulo faz parte de um artigo submetido em 2024 e atualmente em revisão. Neste caso de estudo, apresento descrições a múltiplas escalas – desde abordagem estratigráfica, a análises microscópicas e elementares – de forma a obter dados de alta resolução sobre as estruturas de combustão no sítio em análise. Os resultados mostram que as estruturas de

combustão, duas das quais associadas à mesma camada arqueológica, foram claramente alteradas pós-deposicionalmente por processos biológicos (bioturbação) e geogénicos, principalmente os efeitos de gelo-degelo e solifluxão. Não obstante, há uma variação considerável entre as duas estruturas de combustão. Assim, sugerimos duas hipóteses: 1) as duas estruturas de combustão correspondem a ocupações separadas e diferenciadas em termos temporais que não são discerníveis estratigraficamente, ou 2) as duas estruturas foram criadas durante a mesma ocupação, mas com variações devido a condicionantes ambientais localizadas ou diferenças relativas à organização do espaço durante a ocupação do sítio arqueológico.

No Capítulo 5, apresento um protocolo experimental controlado para examinar o efeito de ciclos repetidos de congelamento-descongelamento na preservação e reconhecimento visual de resíduos e estruturas de combustão em ambientes frios. Processos de flutuação entre períodos de gelo e degelo são extremamente comuns em sítios do Pleistoceno de latitudes setentrionais, muitos dos quais podem ser caracterizados como paisagens periglaciais sujeitas a ciclos sazonais de gelo-degelo. Nesta experiência laboratorial, simulámos 60 ciclos de gelo/degelo em camadas sobrepostas de cinzas e de carvão para observar os efeitos desses ciclos. Durante a experiência, controlámos variáveis como o teor de humidade, posição dos resíduos de combustão (na superfície ou enterrados), o número de ciclos (0, 1, 10, 30, 60) e o tempo de congelamento. De forma a compreendermos os efeitos produzidos, efetuámos uma série robusta de análises estatísticas, análises de micromorfologia e mapeamento elemental por Fluorescência de Raios-X (μ XRF). Os resultados demonstraram alterações mínimas na preservação e reconhecimento dos vestígios de combustão, sugerindo que a falta de preservação pode não ser a razão mais parcimoniosa para as lacunas observadas durante os períodos

glaciais. No geral, estas evidências levam-me a sugerir que o uso do fogo pode não ter sido tão universal quanto assumido, especialmente em épocas e/ou regiões com recursos limitados, com períodos de frio extremo, como o Último Máximo Glacial.

No Capítulo 6, combino os dados dos capítulos anteriores para reavaliar algumas das suposições sobre o uso do fogo no Paleolítico Superior e no Paleolítico como um todo. Destaco como o custo do fogo pode ter superado os seus benefícios durante períodos de stress de recursos. Assim, sugiro que consideremos o chamado registro “invisível” de não uso do fogo no registro arqueológico e o que isso pode significar para reconstruir o comportamento humano do passado. Também proponho uma nova perspectiva sobre como os arqueólogos podem abordar o estudo da pirotecnologia de forma geral. Esta perspectiva assenta sobre um modelo mais fluido que enfatiza a perda e redescoberta repetida da tecnologia de uso do fogo por grupos individuais, em vez de abordagens que assumem perspectivas generalizadas ao nível da espécie humana. Além disso, destaco a necessidade de padronizar e estandardizar as descrições e análises de estruturas para atender a interpretações sobre funções específicas.

De forma geral, esta tese sublinha a importância de estudar a evolução pirotecnológica para reconstruir o comportamento humano e as adaptações do passado. A investigação efetuada fornece novas perspectivas críticas sobre a pirotecnologia durante um período cronicamente negligenciado no Pleistoceno da Europa. Nesta tese, desafio algumas das suposições comuns sobre o uso do fogo por humanos modernos e o que isso significa para períodos anteriores na evolução humana. Além disso, realço a necessidade de descrições mais padronizadas de estruturas de combustão na literatura publicada e integro novos métodos e protocolos para compreender como o uso do fogo é preservado no registro arqueológico. De uma forma geral, esta tese oferece uma base inovadora para

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EPI-AURIGNACIAN, GRA- GRAVETTIAN, PER – PÉRIGORDIAN, GRAV-SOL- GRAVETTIAN-
SOLUTREAN, SOL- SOLUTREAN, SOL-GRAV- SOLUTREO-GRAVETTIAN, MAG –
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Chapter 1

Introduction

The use of fire is one of the most important technological developments in human evolutionary history. In modern times, fire use, either directly or indirectly, is essential to our daily lives. We use fire or its proxies as a practical resource for lighting, warmth, cooking, manufacturing, or protection. We use fire to dispose of trash from our homes and communities. Fire is used as a social resource as well, with fireplaces or campfires acting as a centrepiece where people gather to share information or stories, or to meet with family and friends to share meals and cook together. How fire is used can also vary from culture to culture, with groups using it for ceremonial purposes – such as funerary practices or ritualistic uses –, others for celebrations with the use of fireworks and lightshows. Other fire related developments like the internal combustion engine, power our everyday lives and transport us from place to place. Our daily lives are almost universally dependent on the use of fire and its various proxies. So how did this revolutionary technology develop and when did fire use begin?

From an evolutionary perspective, fire use is widely considered a hallmark of the genus *Homo*, as the production and controlled use of fire are unique to our evolutionary lineage (Sandgathe, 2017; Sandgathe & Berna, 2017). Several scholars have argued the benefits of fire having influenced the biological and social evolution of hominins through the development of cooking (Aiello & Wheeler, 1995; Wrangham, 2017) or the role of combustion features as spatial anchors for social behaviours (Binford, 1978; Chacón et al., 2012; Galanidou, 1997; Rolland, 2004, 2018; Stapert, 1989) With fire use having such an

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important influence on our evolutionary history as well as being an essential part of our daily lives, it is unsurprising that development of fire use as a tool, or Pyrotechnology, has been a centre of fierce debate and fascinating topic of interest in Palaeolithic archaeology particularly in the last 20 years.

This renewed interest has shifted focus of fire use from simple models based on the presence of fire on sites to gathering information about the structures themselves. Several of these studies have focused on the components (Braadbaart et al., 2012; Karkanas, 2021; Karkanas et al., 2002), structural morphology (Lejay, 2018; Mallol et al., 2017; Stahlschmidt et al., 2020), and the preservation of combustion materials (Masson, 2010) in periglacial environments. This coincides with integration of new tools and methods for studying fire use using geological and geochemical techniques (Brittingham et al., 2019; Ferro-Vázquez et al., 2021; Goldberg, 1980; Goldberg & Aldeias, 2016; Goldberg et al., 2017; Leierer et al., 2020; Leierer et al., 2019; Mentzer, 2014), as well as experimental archaeology (Aldeias et al., 2016; Backhouse & Johnson, 2007; Buonasera et al., 2019; Gallo et al., 2021; Lejay et al., 2019; Mallol et al., 2013a; Mallol et al., 2013b; March et al., 2014). This body of literature gives new insights into fire use behaviours and their context.

Much of the current research in fire use in the Palaeolithic is focused on the origins of fire use (Chazan, 2017; Gowlett, 2013; Gowlett, 2016), the development of habitual fire use behaviours in hominins in Europe (MacDonald et al., 2021; Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011; Shimelmitz et al., 2014), and debates over neanderthal fire use (Dibble et al., 2017; Dibble et al., 2018b; Sorensen et al., 2014; Sorensen, 2017). Due to a renewed focus on fire use, several theoretical frameworks have been proposed to explain its development in hominin behaviour. These often revolve around a dichotomy: the perceived gaps in early hominin fire use versus the generally

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accepted ubiquity of fire use by modern humans. Despite this focus, there has been surprisingly little research into the evolution of pyrotechnology during the Upper Palaeolithic (Murphree & Aldeias, 2022), or the preservation of combustion features in periglacial environments that dominated much of the European Pleistocene landscape. Periglacial environments feature seasonal freezing and thawing effecting the landscape. As a result, we currently know more about fire use prior to 50,000 years ago than during the critical period between 50,000 and 15,000 years ago (Murphree & Aldeias, 2022).

This disparity persists despite the widespread assumption that controlled fire use was integral to daily life and survival during cold periods in Upper Palaeolithic Europe. Consequently, our understanding of fire use as a technology in Pleistocene archaeology may be skewed. This obscures potentially unique patterns of adaptation among different groups, populations, and species, and masks periods in the archaeological record where fire use may have been the exception rather than the rule.

1.1 Objectives

The main goal of this thesis is to fill in the knowledge gaps of Upper Palaeolithic pyrotechnology and how it is preserved during cold periods within the archaeological record. As mentioned above, the common perception for fire use in late Pleistocene archaeology is its omnipresence in Upper Palaeolithic assemblages. Any disruption to this pattern can be attributed to anthropogenic, geogenic, or biogenic processes taking place at a site syn- and post-depositionally, that is, during and following human occupations. As such, my thesis has three primary aims:

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- 1) Firstly, this thesis aims to address the evolution and diversification of pyrotechnology throughout the Upper Palaeolithic in Europe. The goal of this broad regional approach is to identify patterns in the types of structures being used and to see how these patterns develop through time and space.
- 2) Secondly, I aim to apply geoarchaeological methods and techniques to study remnants of Upper Palaeolithic fire features focusing on a case-study. For this goal, I will use high-resolution geoarchaeological approaches to reconstruct the formation and post-depositional processes affecting open air fire remains associated with cold environments.
- 3) Finally, I aim to explore the application of experimental archaeology methods, rooted in geoarchaeological approaches, to characterize taphonomical processes that can impact on the visibility of fire residues in the archaeological record. While periglacial conditions, specifically freeze-thaw, are common during the Pleistocene epoch, few studies have focused on how cryogenic processes affect the microstratigraphic integrity of combustion remains.

1.3 Thesis structure and paper status

This thesis includes work that has been published (Chapter 3), submitted for review (Chapter 4) and in final preparation for submission (Chapters 2 and 5). I have subdivided this work into 7 chapters.

Following this initial introductory chapter (1) outlining the objectives and structure of this thesis, I will then present the theoretical and methodological framework forming guiding this research. In chapter 2, I will define the terminology, concepts, and

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methodologies used throughout this thesis. Here, I provide a critical assessment of the theoretical background for how we study the evolution of fire use as a tool in Hominin behaviour – that is, pyrotechnology –, as well as the way these frameworks influence how we study and interpret the European palaeolithic fire use record. I also give an overview of the methodological approaches used in the subsequent chapters.

This is followed by chapter 3, which consists of a review paper titled: “The evolution of Pyrotechnology in the Upper Palaeolithic of Europe” and focuses on the structural evolution of combustion features at 164 Eurasian Upper Palaeolithic sites dated between 48,000- 13,000 years before present (Murphree & Aldeias, 2022). In this paper, we identified several patterns in development of pyrotechnology during the Upper Palaeolithic, as well as gaps in the published descriptions of fire use related to periods of extreme cold during the Last Glacial Maximum (LGM) (Murphree & Aldeias, 2022). This paper was submitted and published in the journal of *Archaeological and Anthropological Science* in September of 2022.

The following chapter 4 is a case study paper titled: “Fire use during the Last Glacial Maximum: evidence from the Epigravettian at Korman’ 9, Middle Dniester Valley, Ukraine”, which provides one of the first high resolution descriptions of fire use during the LGM in Eastern Europe. In this case study, we provide new insights into the use of fire during glacial periods. In doing so, we aimed to help fill in some of the publication gaps identified in chapter 3 as well as give new perspectives on the evidence of fire use in the region. This paper was submitted in October 2024 to the journal of *Geoarchaeology* and is under review. I have provided a modified version of the submitted text to fit into the hybrid manuscript format used in this thesis. There are no changes to the original results or discussion submitted to the journal.

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In chapter 5, I will present the results of an experimental archaeological study aimed at understanding the effects of repetitive freeze-thaw cycles on the preservation and recognition of combustion residues. This chapter is currently in final preparation for submission and is under revision with co-authors. Again, this chapter has been slightly modified in this thesis to fit the overall structure of the hybrid monograph, but the contents, results, discussion, and conclusions are consistent with what will be submitted.

In chapter 6, I will address what the current evidence on Upper Palaeolithic fire use means to our understanding of the evolution of fire in human behaviour. I will also address limitations of this study, as well as discuss future avenues for research in Upper Palaeolithic fire use.

Finally, in chapter 7, I will summarize the general findings for this work and its place in the study of pyrotechnology. These chapters, along with sections of chapter 2, are in preparation for submission as a theory paper.

1.4 Data Availability.

To fit the open access policies of ICArEHB, all papers and data within this thesis is published or will be published in an open access repository. The supplementary files for each chapter are available at the end of this text and will be available online. This includes all databases and high-resolution images files for all figures in the text.

Chapter 2

Theoretical framework

2.1 Introduction

The basis of how we study and interpret fire related behaviour is rooted in theory and definitions. Many of which are – unfortunately - poorly defined, non-standardised, or as stated in the previous chapter based on a diametric relationship contrasting the limited evidence of early fire use in the Eurasian record with assumptions made of modern human behaviour. Additionally, many of the interpretations we make about the evolution of fire use is linked to other material culture which provides a generalised view of the past, while potentially obfuscating outliers in fire use behaviour.

In this chapter, I will define several of the terms used throughout this thesis and address the theoretical basis for them. I will give a critical assessment of the primary theoretical frameworks used to describe the evolution of fire use in the Pleistocene of Europe. I will also address several perceptions and assumptions about fire use that is driving much of the debate over the development and utilization of fire in hominin behaviour. In doing so, I will present a conceptual structure that connects the results of following chapters to the discussion at the end of this thesis.

Additionally, I will provide a generalized overview of the methodologies, and their theoretical basis used throughout this thesis. The goal of this section is not to repeat the individual methods sections for each of the following chapters. Instead, I give a framework for why I am approaching the study of fire this way and how the application of

geoarchaeological methods and techniques expand and improve upon archaeological interpretation of fire use in human behaviour.

2.2 The boxes we use to define ourselves

In archaeology, we uncover, study, and analyse material culture or features left behind by past people to interpret their behaviour (Miller, 2011; Renfrew & Bahn, 2013). In doing so, we try to understand questions about how people lived, how they interacted with their environment, what they ate, where they lived, how they shaped the world around them and how the answers to these questions changed through time. We do this by classifying what we find in groups with shared attributes or features. In turn, we organize these groups hierarchically based on shared attributes, context, and chronology, which we then use to make our interpretations of the past. This is the basic framework for most western scientific thought, and it is one that archaeologists, especially those focused on the Palaeolithic, both excel and fail at.

Accordingly, the current paradigm for how we study the evolution of fire use in Palaeolithic archaeology has generally been a mirror of how we view and study other material culture in the archaeological record. Although the nature of combustion materials varies considerably from other forms of cultural remains, as these are “non-portable” artifacts (Miller, 2011; Renfrew & Bahn, 2013), we generally still follow similar theoretical frameworks as those established for other materials and technologies (e.g., Allué et al., 2022, p. 235). This theoretical paradigm reflects the change in focus for much of the fire-related research in the last 20+ years to the structures themselves rather than

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their presence in an site or as spatial markers around which human activity is organized (Binford, 1980; Galanidou, 1997; Goldberg et al., 2017; MacDonald et al., 2021; Roebroeks & Villa, 2011; Rolland, 2018; Sandgathe et al., 2011; Stapert, 1989). It also corresponds to the use of newer analytical methods and techniques that provide new insights into the evolution of fire use behaviours (Brittingham et al., 2019; Ferro-Vázquez et al., 2021; Goldberg & Aldeias, 2016; Herrejon-Lagunilla et al., 2024; Leierer et al., 2019).

In much of the available literature on fire use, the terms used to describe combustion related structures vary considerably with no clear consensus. Terms like hearths, fireplaces, combustion areas, or fire features are commonly used throughout much of the published literature (Murphree & Aldeias, 2022). While these are all correct, in the sense that they describe a location where humans used fire, they imply a structure is intact or “in-situ”, which might not accurately reflect the reality at a site (Goldberg et al., 2017; Mentzer, 2014). Some remains of anthropogenic fire use are not in their original position in which the terms “hearth or fireplace do not accurately reflect the evidence. Moreover, terms such as “hearth” or “fireplace” have also an implied associations with human activities taking place around them. This interpretation often reflects the motto, “*home is where the hearth is*” (Galanidou, 1997; Rolland, 2004) and suggests a direct link between the combustion activities and the nearby material culture as related activities. This theoretical association may not reflect the reality in some cases.

An all-encompassing term to simply describe the archaeological remains of fire use is combustion features. Combustion features are defined by Mentzer (2014) as remains of anthropogenic fire use both in an intact position, i.e. fireplaces or hearths, and in secondary position due to geogenic and/or biogenic processes, or human action. Combustion features are also sedimentary artifacts created via direct human action

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(Goldberg et al., 2017; Miller, 2011). As a result, are highly susceptible to syn- or post-depositional processes that can obscure or disrupt completely the preservation of combustion remains. For instance: site cleaning can remove ash and charcoal from a combustion feature depositing them in different areas (Miller et al., 2010; Schiegl et al., 2003a), or humans can remove combustion materials to access shellfish after cooking (Aldeias et al., 2019). The presence of organic-rich combustion remains also can promote biogenic activity from soil fauna or plants (Schilt et al., 2017), or can be altered and removed by different geogenic processes (Goldberg et al., 2017; Karkanas et al., 2000; Karkanas et al., 2002; Mallol et al., 2013b; Masson, 2010; Texier et al., 1998).

To further muddy the waters of defining the evidence of human fire use in the archaeological record, there are also several indirect proxies, such as presence of burned lithics, burned bones and charcoal, which have been used to indicate fire use at sites where combustion feature are not preserved (e.g., Abdolazadeh et al., 2022; Alperson-Afil, 2008; Cutts et al., 2019; Hlubik et al., 2019; Sorensen & Scherjon, 2018; Zohar et al., 2022). While these approaches are again valid methods to determine if there was fire present; there still remains a burden of proof that needs to be demonstrated to say that: A) fire residues reflect human agency and are not related to natural fire events and B) it is directly related to the proxies being used (i.e. thermally altered artifacts) (Goldberg et al., 2017). With issues such as time averaging, understanding the contemporaneity between the use of fire and other behaviours at a site can be problematic, especially in older excavations where more modern methods were not used, and where we lack temporal or stratigraphic resolution (Dibble et al., 2016; Dibble et al., 2009). Moreover, as heat from burning is transferred downward, it can thermally alter buried materials which can mirror intentional burning (Aldeias et al., 2016). Finally, as fire is both a natural and

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anthropogenically derived phenomenon, it is up to the archaeologist to demonstrate that burned materials are a result of human activity (Barbetti, 1986; Goldberg et al., 2017). To put it simply: the presence of fire remains alone does not mean that humans used fire. Apart from natural fire remains, there have been cases where natural process might mirror fire remains (Goldberg et al., 2001; Nejman et al., 2018; Nejman et al., 2017; Stahlschmidt et al., 2015). While this paints a not so promising picture for how we identify and interpret fire use in the past, especially further into the past we go, it nonetheless is essential for understanding some of the challenges facing our interpretations on the evolution of this behaviour in hominins based on the available archaeological evidence.

As stated above, when considering patterns in the evolution of fire use in hominins, we tend to attach ourselves to other forms of material culture where frameworks and analytical systems are better established and have longer research histories. Archaeology is a multidisciplinary field incorporating different parts from different disciplines to study the past, so it is no surprise that this is the case with fire use. Palaeolithic archaeology is a field that has, until arguably recently (Aldeias & Stahlschmidt, 2024), been dominated by understanding the relationships, interactions, and behavioural evolution of hominins through the lens of stone tools. Stone tools or lithics and the related debitage (refuse created during the creation of stone tools) are by far the most numerous and durable material culture remains in the Palaeolithic record. Variations in how lithics were made, tool types, raw materials, and perceived functions have been used to differentiate between species, populations and groups throughout Eurasian Pleistocene archaeology, as well as provide a chronostratigraphic marker for different groups occupying the same place (Dibble et al., 2016; Foley & Lahr, 2003). For instance, from the presence of Mousterian stone tools - flake based reduction tool technology -, we can infer

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that Neanderthals were occupying a site, while the presence of Aurignacian tools -blade and laminar reduction method- are thought to be a clear marker for early modern humans. When looking at the broader picture, lithic industries or technocomplexes provides the illative framework of how we understand and discuss the past. The distinctions between lithic typologies, reduction sequences, mobility, resource acquisition, etc, have become the groups or complexes that we also link other behaviours with to formulate our interpretive narratives on the evolution of hominin behaviour. For example, when we use a term related to a distinct technocomplex, like the Gravettian, we automatically associate certain behaviours, traits, and material culture to a distinct population and time frame in the Upper Palaeolithic. In this sense, the Gravettian is much more than a lithic industry but a marker for a distinct population (Fu et al., 2016), with shared sets of behaviour (Kozłowski, 2015; Otte et al., 1996; Wilczyński et al., 2021) spread across Europe. While the study of lithics is dynamic in terms of methodologies, the framework and boxes we place them in are generally not (Rolland & Dibble, 1990; Shea, 2014). Much of the nomenclature used for industries or technocomplexes have been recycled or reused throughout the history of Palaeolithic archaeology (Foley & Lahr, 2003; Shea, 2014, 2016). This gives lithics and their associated behaviours a sense of permanence and stability as an organising principle for how we look at behaviour in the archaeological record.

It then comes as no surprise that when viewing other technologies, like using fire, we adopt lithics as a framework to build our own lines of inquiry (Allué et al., 2022). In someways we are mirroring lithics studies, in terms of looking at how fires were lit (Sorensen et al., 2018), the types of fuels used (Costamagno et al., 2009; Théry-Parisot et al., 2009), typologies for structures (Mallol et al., 2017), and effects of fire use on mobility

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and resource acquisition (Henry, 2017; Pryor et al., 2016). We use associations with certain industries and technocomplexes to explain or make assumptions about the presence or absence of fire use behaviours (Dibble et al., 2017; Dibble et al., 2018b; Sorensen, 2017) or structures present (Murphree & Aldeias, 2022). We also use theories regarding the spread of lithic technology as the potential mechanism for knowledge transfer for fire use (MacDonald et al., 2021; Roebroeks & Villa, 2011; Sorensen et al., 2014). For better or worse, we are currently handcuffed to lithics as the organizing basis and principle for exploring the evolution of hominin fire use and behaviour in Pleistocene archaeology.

With this said there are several fundamental issues that binding fire use to lithics has created when building interpretive models for the evolution of fire use. One of which is the tendency to adopt a generalised version of behaviour or embedding fire use in a behavioural complex without meriting its own set of conditions and limitations. A prime example of this has been the debates over decrease in fire use by Neanderthals in Western France during cold periods (Dibble et al., 2017). In their 2017 and 2018 papers, Dibble et al., (Dibble et al., 2017; Dibble et al., 2018b), contend that this decrease in fire use is due to a lack of available natural sources of fire. This implies that the Neanderthal groups occupying the sites in question were not obligate fire users or lacked the ability to make fire on their own. These findings were refuted by a series of papers by Sorensen and colleagues (Sorensen, 2017; Sorensen, 2024; Sorensen et al., 2018). From a theoretical perspective, this debate forms interesting questions about how we explain and interpret the past and apply those assumptions in academic discord. Can we assume that, because a behaviour is present at other sites, obligate fire use is a norm within neanderthal behaviour? Or is the use of fire more variable depending on the individual groups with their own knowledge or choices or even depending on the environments they inhabit

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(Dibble et al., 2018b; Sandgathe, 2017)? Essentially, this can be boiled down to if we clump behaviours together as overall trends/ technocomplexes or if there are more regional or localized patterns of behaviour within a given technocomplex.

The former line of thinking is persuasive throughout most theoretical frameworks used for interpreting fire use in Palaeolithic archaeology. Currently there are two primary models for interpreting the evolution of fire use in hominin behaviour, shown in Figure 1. The first is a four-step model, which separates the development of fire use behaviour into four successive steps: (1) habituation to natural fire, (2) opportunistic use of fire from natural sources, (3) control of fire via refuelling, transport and maintenance, and finally (4) the production of fire through artificial means (Allué et al., 2022; Chazan, 2017; Gowlett, 2013; Gowlett, 2016; Sandgathe, 2017; Sorensen, 2019). This model is considered a discovery-based system, where once a group or populations discover they can utilize fire, the behaviour becomes commonplace within the behavioural lexicon of hominins and evolves in a linear pattern of increasing complexity. The mechanism for this transference of knowledge is not well understood, although several models based on archaeological and ethnographic examples have been proposed to explain how the knowledge of fire use was passed from one group to another (MacDonald et al., 2021; McCauley et al., 2020; Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011). The second model is a multistep more gradual, non-directed model (Allué et al., 2022; Chazan, 2017; Gowlett, 2016; Sandgathe et al., 2011). It includes the conceptualization of fire, opportunistic use of natural fire sources, maintenance of natural fire, habitual use of fire, fire making via artificial means, and finally the transition of fire use from a natural to cultural resource (Allué et al., 2022; Chazan, 2017; Sandgathe, 2017). The strength of this model is that it avoids the implied linear direction of progress that the former model is dependent on.

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However, as stated by, Allué et al. (2022, p. 229) it is unclear when these behaviours evolve or what species these behaviours can be linked to, and what the impact these behaviours have on the cultural and biological evolution of hominins.

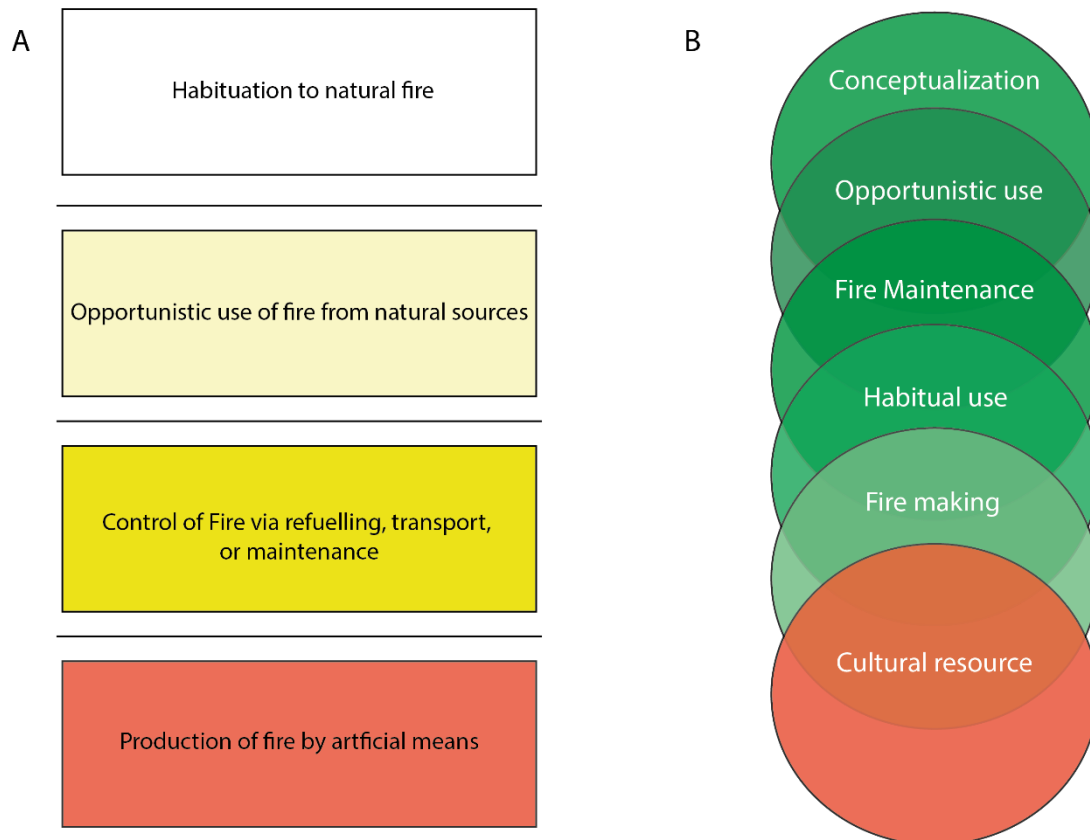


Figure 1: Theoretical models for explaining the development of fire use behaviour in hominin evolution. A) Four stage model. B) Multistep, gradual, non-directed model.

What is a key underlying theme from both models is the use of so-called knowledge thresholds to explain the progression of fire use behaviours and links between behaviours, populations, and species. In other words, once a group – or in most cases species – achieves the ability to use fire or create fire via artificial means, essentially passing from one box to another, they do not go backwards. As stated by Sorensen (2019), “once having acquired the ability to make fire, it is unlikely that this exceptionally useful

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tool would simply have been forgotten by Neanderthal or other hominin groups, barring very exceptional circumstances (e.g., local extinction shortly after discovery)"(pg. 22). This is a common enough sentiment within the fire use research community. It is also one seemingly entangled or enhanced by the overall paradigm in Palaeolithic archaeology. As stated above, we generally explain and interpret the past based on the presence of lithics. In doing so we use technocomplexes to organise past behaviours (including fire use) and make hierarchical comparisons between groups. Essentially creating boxes to study the past. Therefore, there has been a trend to dismiss outliers, such as in the case with the Western Neanderthals, as against the norm (Sorensen, 2017; Sorensen, 2018) rather than a potentially unique adaption by a distinct group or local population because they share other facets of technology (lithic tool types) (Brittingham et al., 2019; Dibble et al., 2018b; Sandgathe, 2017).

The ability to start fires is not a given in any hominin species. In a recent ethnographic study of the use of fire by modern hunter gatherer groups by McCauley et al. (2020), the authors found evidence in some groups of the loss of the ability to make fire artificially or that fire making was not a universally shared skill within the groups themselves (i.e. restricted to individuals). While the ethnographic studies are not direct analogues, it can inform and create interpretive avenues that should not be ignored for the sake of simplicity. It is quite possible that, by generalizing behaviour and continually focusing on explaining the larger picture, we have dismissed trends, behaviours, and adaptations in hominin evolution, especially in the case of fire use, as outliers rather than unique patterns within a larger framework.

Looking beyond the issues of generalizing fire use behaviour with technocomplexes, there are several other key issues in how we interpret fire use in human

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behaviour that need to be considered in more detail. The first is linking the presence of combustion features to an occupation surface or “living floor” (Dibble et al., 2016). Several studies have focused on looking at the spatial dynamics and social organization of hominins using combustion features as a spatial anchor or hub (Chacón et al., 2012; Galanidou, 1997; Rolland, 2004, 2018). As stated by Dibble et al. (2016), understanding the concurrence of fire use and other behaviours within the same occupational layer or horizons can be problematic. Occupational remains within a single horizon can represent a single visit to tens, if not hundreds of different visitations by the same or differing groups over a long-time scale. With issues like time averaging, the presence of fire remains with other material cultural is not necessarily linked and could be separated on a scale of days to millennia (Herrejon-Lagunilla et al., 2024). This reflects the so-called Pompeii premise, discussed by Binford (1981) and Schiffer (1985), in which archaeologist look for an idealized pristine site or “*in-situ*” behaviour (Dibble et al., 2016). However, this likely does not reflect the reality as every site has undergone combinations of site formation processes to varying degrees over time (Schiffer, 1972, 1987). This in turn, creates differing degrees of preservation and limits the interpretations we can make between the different behaviours within the same layer or horizon (Dibble et al., 2016; Schiffer, 1972). This is not to completely dismiss the relationship between fire use and material culture within the same layer. In fact, it creates a unique avenue for future research that will be discussed further in Chapter 6.

Another significant factor is the cost of fire, which encompasses resource use, labour, and time, along with its impact on mobility and hominin behaviour. Fire use is a costly investment (Henry, 2017; Pryor et al., 2016). While estimates for fuel use are difficult to assess based on archaeological or ethnographic data, the estimates can range from 5-

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25 kgs a day to over 100 kgs a day depending on factors like: the hearth size, construction, type, function, weather, fuel types and conditions, burning time, etc. (Binford, 1978; Gowlett et al., 2012; Mallol et al., 2013a; Pryor et al., 2016). This alone implies that fuel collection had a major impact on hominin behaviour including labour distribution, site selection, and resource management. Moreover, archaeological evidence suggests the quality and types of fuels available played a key role in mobility and where people lived within a landscape even in earlier periods than the late Pleistocene (Brittingham et al., 2019; Leierer et al., 2019). This prospect raises several questions as it is unclear when hominins switched from opportunistic (using the available fuels around them) to intentional selective fuel acquisitions. These can include: if this is a localized adaptation or if the relationship between hominins groups and fuel selection is more fluid, varying depending on natural (climate, environment, resource availability within a region) or cultural (knowledge of local resources, needs, group preferences, or social organization) factors. It also suggests that if fire use is an essential adaptation in hominin behaviour, then the ability to access, collect, and manage reliable fuel supplies dictated mobility on a daily basis. Further research is needed to better understand the relationship between hominins, fire use, and fuel selection as a function of social organization. Overall, the take home message is that the benefits generally must outweigh the cost for fire use to become a habitual behaviour.

In a similar vein, there is a general lack of fire-starting tools in the archaeological record (Sorensen, 2019). The poor organic preservation at many sites means that the likelihood of finding plant-based fire making tools, like friction tools, is highly unlikely (Sorensen et al., 2014). Moreover, the evidence of lithic percussion-based methods is, while intriguing, extremely difficult to identify in the archaeological record as edge

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damage after 40,000 year is extremely variable (Sorensen et al., 2014; Sorensen et al., 2018). The lack of fire making tools makes any inferences regarding the production of fire at will extremely problematic, especially the further back into time we look. When also taking in account, ethnographic data and accounts of modern human hunter gatherers lacking the ability to create fire on their own, being dependent on natural sources, or maintaining and transporting embers from place to place, it is difficult to estimate the prevalence of fire making in the Palaeolithic (Mallol & Henry, 2017; Mallol et al., 2007; McCauley et al., 2020).

Overall, the evidence for fire use in the Palaeolithic compared to its supposed impact in hominin biological and social evolution is sparse and problematic at best (Chazan, 2017; Sandgathe, 2017). This is not to say that fire use did not have a major influence on how our genus evolved through time, but it is also possible that fire's role has been overstated in the current literature. Much of this has, in many ways, been caused by overgeneralizing behaviour in Palaeolithic archaeology by grouping behaviours into technocomplexes. Notwithstanding, the general lack of taking into account the cost of such a behaviour and the patchy evidence for fire behaviour until the late Pleistocene would clearly factor into if fire use was an obligate or habitual behaviour or not (Sandgathe, 2017; Sandgathe et al., 2011). Questions should be asked of so-called outliers or variability in fire related behaviour and when do these outliers effectively become a norm. As stated by other authors, the knowledge of fire use was likely lost and rediscovered multiple times over the course of the Pleistocene by several different groups, populations, and species (Sandgathe, 2017). This would imply that evolution of fire-related behaviours is much more dynamic and fluid than much of the current literature implies. It is also quite likely that we overestimate the impact and importance of fire based on our

own behaviour and the assumptions we have placed on the fire use behaviour in the Upper Palaeolithic which is addressed below.

2.3 The evolution of fire use behaviour and the Upper Palaeolithic

A repeated argument used in interpreting the development of fire-related behaviours by hominins or interpreting gaps in the archaeological record in the middle to late Pleistocene, is using assumptions about Upper Palaeolithic fire use as a backstop to compare patterns from earlier periods. In other words, while behaviour "A" is not present or as common in the Middle Palaeolithic, it is well established in modern human behaviour (Dibble et al., 2018b; Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011; Sorensen et al., 2014).

Currently, the widely accepted view in Palaeolithic archaeology is that fire use is ubiquitous in modern human behaviour (Chazan, 2017; Goldfield et al., 2018; Roebroeks & Villa, 2011; Sandgathe, 2017; Sorensen, 2019). As such, there are clear implications for fire use to be a ubiquitous technology: 1) Modern humans must have had the ability to produce fire at will or at the very least not fully dependent on natural sources, 2) modern humans are dependent on daily fire use, and 3) evidence for fire use is almost universally present in the Upper Palaeolithic sites, and only lacking when preservation is poor. As discussed above, it is difficult to determine the validity of the first implication because of the lack of preservation of fire making implements (Sandgathe, 2017; Sorensen, 2019). Some lithics or so-called strike-a-light implements have been proposed using use-wear analysis (Sorensen et al., 2014). However, it is unclear how widespread this technology is in

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Palaeolithic assemblages or how identifiable other fragments would be if lithics were reused or recycled for other purposes (Dibble et al., 2016). The second and third implications go relatively hand in hand. Both are generalized statements based on a combination of the assumed relative abundance of fire structures in the Upper Palaeolithic compared to earlier periods; and, I would argue, also as a potential projection of our own current dependency on fire use. Currently, we do not have a clear idea what is the true extent of modern human fire use in the Upper Palaeolithic.

There also has only been limited work done looking at the effects of frost related processes – common throughout most northern latitude sites during the Pleistocene in Eurasia - on the preservation of combustion features. Overall, there has been very little research focused on Upper Palaeolithic fire use in comparison to earlier periods. This needs to be addressed before we can make big assumptions about evolution of fire use in the European Pleistocene record.

2.4 Studying fire use in Palaeolithic assemblages

How we approach studying and understanding fire use in Palaeolithic assemblages has evolved rapidly in the last 20 years with the integration of new methods and techniques. In this study, I approach studying the remains of fire use using a geoarchaeological framework. This framework incorporates methodologies, techniques, and interpretational applications developed in the geosciences to answer archaeological questions (Miller, 2011, p. 92). Geoarchaeology focuses on understanding material remains of human behaviour in their geological and environmental context. In archaeology,

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context is everything and, by focusing on the sedimentary matrix and processes that form it, we can then better inform our archaeological interpretations of past human behaviour (Miller, 2011; Schick, 1986; Schiffer, 1987). It also allows us to see how past humans influenced the world around them including the geology and environment they lived in (Miller, 2011).

In terms of fire use, the remains of combustion features are sedimentary artifacts (Goldberg et al., 2017; Miller, 2011). This term was defined in the section above, but I have chosen to use it again to point out that, unlike other “portable” artifacts, once combustion remains are removed from their primary context, it erases much of the important anthropogenic actions which form the deposit (Goldberg et al., 2017; Miller, 2011). As such, much of this thesis is focused on the structural morphology of combustion features, looking at shape, composition, and surrounding context. Throughout this thesis, I use multiscale descriptive analytical methods to describe combustion features and their context in high detail. This includes archaeological soil micromorphology as the backbone of this thesis.

Micromorphology is a method of analysis of thin sections of intact sediments originally developed in the early 20th century in soil sciences (Kubiëna, 1939) and then adapted for studying archaeological sites and features in 1950’s (Courty et al., 1989; Goldberg, 1979, 1980). The advantage of this method is that it preserves and maintains the sediments and archaeological remains as they were in the original deposits. This means that the geometry and spatial relationship between sedimentary matrix, including anthropogenic components, remains intact during analysis. In turn, this allows for the assessment of the context of the anthropogenic features, including important information regarding how the features were formed, their composition and how the remains

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changed through time (Goldberg, 1980; Goldberg & Aldeias, 2016; Goldberg & Berna, 2010; Mallol et al., 2013b). This is especially important for structures like combustion features as our primary source of information for understanding how they were made and what they were potentially used for is contained in the sediments themselves. Another advantage of using micromorphology is that also allows the detailed studied of the components, not only in terms of identifying what is in the combustion feature but how they fit together (Miller, 2011). This gives use important information regarding interpreting possible functions of combustion features than more traditional macroscopic descriptions are unable to assess. The use of micromorphology to study fire use has become more prevalent in the last 20 years and has been instrumental in identifying combustion structures (Mallol et al., 2013b), previously unseen behaviours- .e.g. dumping of ash remains (Miller et al., 2010; Schiegl et al., 2003b)-or re-examining remains misinterpreted as fire use in the archaeological record (Stahlschmidt et al., 2015).

However, as surmised by Goldberg & Aldeias (2016, p. 274) micromorphology cannot work in a vacuum and not without integrating data from a larger scale of analysis. Moreover, micromorphology is not the only method that can be used to study fire from a micro-contextual perspective. Recent studies using biomolecular markers, microscopic X-Ray Fluorescence (μ XRF) elemental mapping, and infrared spectroscopy among many other methods are giving new and exciting insights into fire use that cannot be ascertained using traditional visual descriptions alone (Berna, 2017; Brittingham et al., 2019; Fernández-Palacios et al., 2023; Herrejon-Lagunilla et al., 2024; Leierer et al., 2019; Mentzer, 2017; Weiner et al., 2015).

Throughout this thesis, I incorporate descriptions of combustion features based on macroscopic and microscopic analytical methods. This ranges from field descriptions,

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including feature dimensions, shape, and presence of different components and their nature, to microscopic observations. However, as shown in chapter 3, the descriptions, and methods we use to describe combustion features in archaeological assemblages lack standardization. This greatly effects how we can currently interpret fire related behaviours. Moreover, as excavation methods and standards have changed greatly over the last 150 years, and can vary regionally based on research traditions, it quite difficult to identify and interpret patterns in fire use over time. As such, in chapter 3 we propose a more standardized method of describing combustion features which I follow throughout the rest of the thesis.

Despite the methodological choices made in this thesis, it should be noted that archaeologists study fire use within various frameworks, not solely within a geoarchaeological context. Other significant studies have been conducted looking at the presence of fire features or their proxies in archaeological assemblages (Alperson-Afil, 2008; Bosch et al., 2024; Bosch et al., 2012; MacDonald et al., 2021; Roebroeks & Villa, 2011; Sandgathe et al., 2011; Wrangham, 2017). Others incorporate ethnographic resources to study the use of fire in modern hunter gatherer populations (Binford, 1978; Binford, 1980; Mallol et al., 2007; McCauley et al., 2020). Overall, it takes a multidisciplinary approach, incorporating viewpoints and perspectives from various fields and approaches to understand fire use and its influence on human behaviour and evolution. While throughout the next few chapters of this thesis, I follow a geoarchaeological framework, I do incorporate data collected from the studies mentioned above, among several others, to give a broader picture to understand fire use in the Upper Palaeolithic.

Chapter 3

The Evolution of Pyrotechnology in the Upper Paleolithic of Europe

Authors: William Chase Murphree¹, Vera Aldeias¹

Affiliation: ¹Interdisciplinary Center for Archaeology and the Evolution of Human Behavior (ICArEHB), University of Algarve, Faro, Portugal

Corresponding author: Vera Aldeias: vlaldeias@ualg.pt

Abstract:

Pyrotechnology, the ability for hominins to use fire as a tool, is considered as 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 characterising 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 to 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 to 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-

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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

3.1 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, it's 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, i.e., how combustion

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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 & 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., 2018b; 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.

3.2 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;

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Dibble et al., 2017; Goldberg et al., 2012; Goldfield et al., 2018; Mallol et al., 2019b; Rigaud et al., 2015; Roebroeks & Villa, 2011; Rosell & 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., 2020; Hublin et al., 2020), fire use is considered to be ubiquitous and fundamental part of AMH daily life (Chazan, 2017; Pryor et al., 2016; Roebroeks & 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 & Henry, 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 to 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 & Wrangham, 2013; Stahlschmidt et al., 2015), though they remain few and far between. After 400 Ka BP, the direct evidence of anthropogenic fire use, i.e., combustion features, while still very limited, is more apparent within the archaeological record (Roebroeks & 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 & Villa, 2011).

Combustion features - i.e., a 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 artifacts with a structural variation formed directly from human action (Mentzer, 2014; Miller, 2011). The detailed descriptions of the morphology and

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composition of combustion features, i.e., their shape, components, and context, are invaluable sources of paleoenvironmental information (Mallol & 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 & Henry, 2012), heat altered lithics (Abdolahzadeh et al., 2022; Plavšić et al., 2020), as well as via ethnographic (Friesem, 2016; Mallol & 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 under-utilized, 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; Jambriña-Enríquez et al., 2019; Leierer et al., 2020; Leierer et al., 2019; Mallol et al., 2019a; Mallol et al., 2013a; Pérez et al., 2017; Roebroeks & Villa, 2011). There are also considerable debates concerning if 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., 2018b). The current evidence of fire use at Middle Palaeolithic sites suggests Neanderthals primarily built flat, unlined combustion features (Leierer et al., 2020; Leierer et al., 2019; Mallol et al., 2013b; Marcazzan et al., 2022), though there is also limited evidence for the potential use of pit features, i.e.

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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 Hayonmin in Israel (Albert et al., 2012; Goldberg & 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; Dibble et al., 2018b). 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 scaled 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., 2020; 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., 2012a; 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 (Bulus & Conard, 2001). The subsequent Middle Upper Palaeolithic (MUP)

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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; Svoboda et al., 2015; Svoboda et al., 1997; Svoboda et al., 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 & 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 & 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 & 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 & 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;

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Schiegl et al., 2003a; White et al., 2017) or variations in hearth components like fuel sources (Buonasera et al., 2019; Costamagno et al., 2009; Henry & Théry-Parisot, 2014; Marquer et al., 2010; Théry-Parisot et al., 2005; Yravedra et al., 2016; Yravedra & Uzquiano, 2013). Moreover, the wide methodological variety in excavation strategies, sampling methods, descriptions, and regional research biases, have 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.

3.3 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 Spanish.

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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

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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 S.I- Chapter 3. 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

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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 (S.I.- Chapter 3). 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

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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.

3.4 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.

Table 1: List of Category 1 sites reviewed, where MP- Middle Palaeolithic, IUP- Initial Upper Palaeolithic, Boh- Bohunian, 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- EpiGravettian. Sites ranked as categories 2 and 3 are discussed in the text and plotted in figures 2, 4, and 5.

	Site Name	Country	Fire Present	Reference
1	Langmannersdorf	Austria	EpiAu	(Salcher-Jedrasiak et al., 2010; Verpoorte, 2004)
2	Saladorf/	Austria	Gra	(Simon & Einwögerer, 2008)

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	Perschling			
3	Ollersdorf	Austria	Gra	(Antl-Weiser, 2008)
4	Alberndorf	Austria	Late Au	(Steguweit & Trnka, 2008)
5	Berdyzh	Belarus	Gra	(Klein, 1974; Soffer, 1985)
6	Siuren I	Crimea	Au	(Demidenko & Otte, 2000; Demidenko et al., 2012)
7	Stránská skála	Czechia	Au	(Svoboda, 2006; Svoboda & Bar- Yosef, 2003; Tostevin, 2003; Valoch, 2013)
8	Líšen I/ Líšeň – Čtvrtě	Czechia	Au	(Demidenko et al., 2017; Škrdla, 2017a; Škrdla et al., 2016)
9	Vedrovice V	Czechia	Au	(Demidenko et al., 2017; Oliva, 1989a; Škrdla, 2017a; Škrdla et al., 2016)
10	Líšeň VIII / Líšeň – 38yr výhonem	Czechia	Au	(Škrdla, 2017a; Škrdla et al., 2016)
11	Podoli V	Czechia	Au	(Demidenko et al., 2017; Škrdla, 2017a; Škrdla et al., 2016)
12	Napajedla III	Czechia	Au	(Demidenko et al., 2017; Škrdla, 2017a)
13	Mladec cave	Czechia	Au	(Svoboda, 2001; Teschler- Nicola, 2007)
14	Orčechov IV	Czechia	Boh	(Škrdla, 2017a; Škrdla et al.,

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				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 & Nerudová, 2010)
20	Pod Hradem	Czechia	MP, Sze, Au	(Nejman et al., 2018; Nejman et al., 2017)
21	Isturitz	France	Au	(Barshay-Szmidt et al., 2018b; 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 & de

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				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, 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 & Miskovsky, 1983; Roussel & Soressi, 2010a)
36	Abri de la Souquette	France	EUP	(White et al., 2017)
37	Roc de Combe	France	Gra	(Grayson & Delpech, 2008; Zilhão & d'Errico, 1999)

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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 & 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)
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-	Germany	Au	(Moreau & Terberger, 2019)

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	Seulberg			
53	Wiesbaden- Ilgstadt	Germany	Au	(Street & 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 & 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)

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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., 2015a)
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 & Sampaio, 2003a, 2003b; Sellami, 2009)
77	Romanesti-Dumbravita I	Romania	Au	(Schmidt et al., 2013)
78	Mitoc Malu Galben	Romania	Au, Gra	(Nigst et al., 2021; Noiret & Otte, 2010)
79	Tibrinu	Romania	EpiGra	(Anghelinu et al., 2018; Marin 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	(Anikovich et al., 2007)

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83	Borschevo 5	Russia	Gra	(Lisitsyn, 2015)
84	Kostenki 13	Russia	Gra	(Sinitsyn & Sanz, 2015)
85	Kostenki 11	Russia	Gra	(Pryor et al., 2020a; Sinitsyn & Sanz, 2015)
86	Kostenki 4	Russia	Gra	(Sinitsyn & Sanz, 2015; Zheltova, 2015)
87	Kostenki 8	Russia	IUP	(Sinitsyn & 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 & Simán, 1989)
92	Barca II	Slovakia	Au	(Svoboda & Simán, 1989)
93	Moravany-Lopata	Slovakia	Gra	(Pawlikowski et al., 1998)
94	Trencianske Bohuslavice	Slovakia	Gra	(Kaminská, 2016; Vlačiky et al., 2013)
95	Potočka Zijalka	Slovenia	Au	(Verpoorte, 2012)
96	Cova Foradada	Spain	Au	(Morales et al., 2019)
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)

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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	Beregovo	Ukraine	ProtoAu	(Usik et al., 2014)

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 (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).

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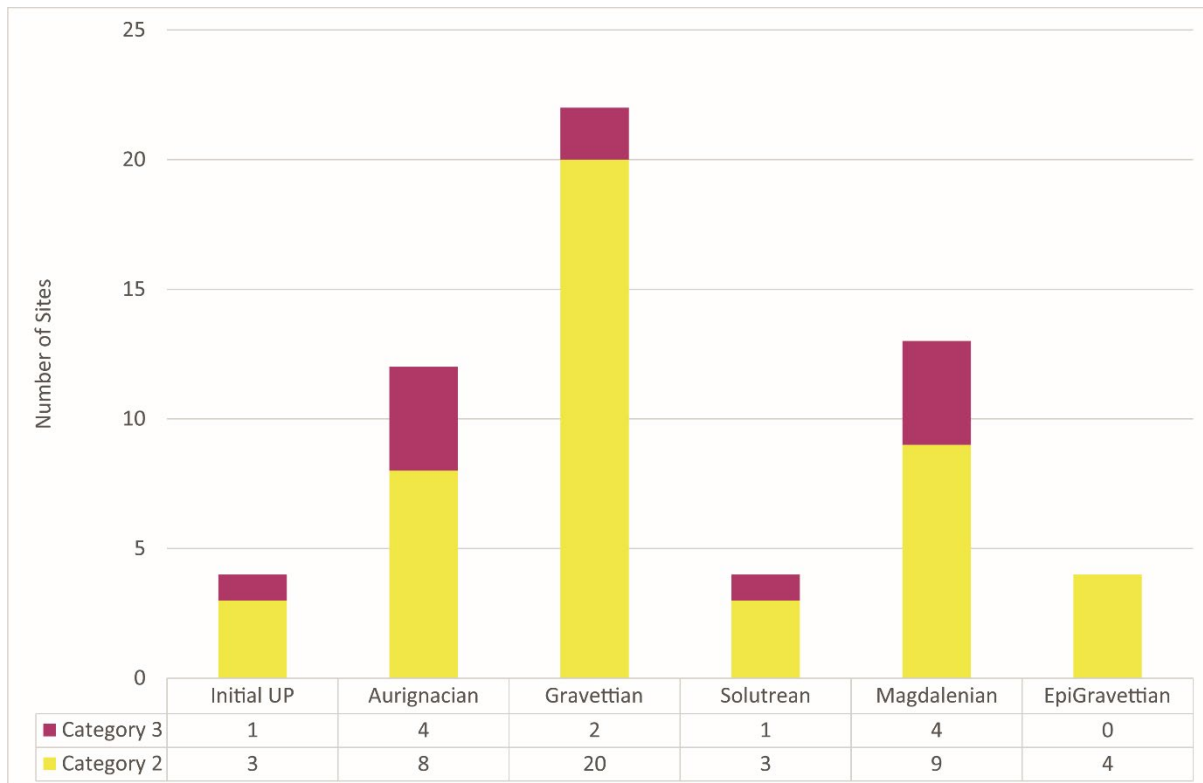


Figure 2: Distribution of categories 2 and 3 sites and cultural associations of fire evidence. Sites with fire evidence associated to multiple technocomplexes appear more than once.

As shown in Figure 2, 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 Figure 3, 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

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observations alongside higher-resolution analysis of the formation history of combustion features (purple symbols), remain particularly rare.

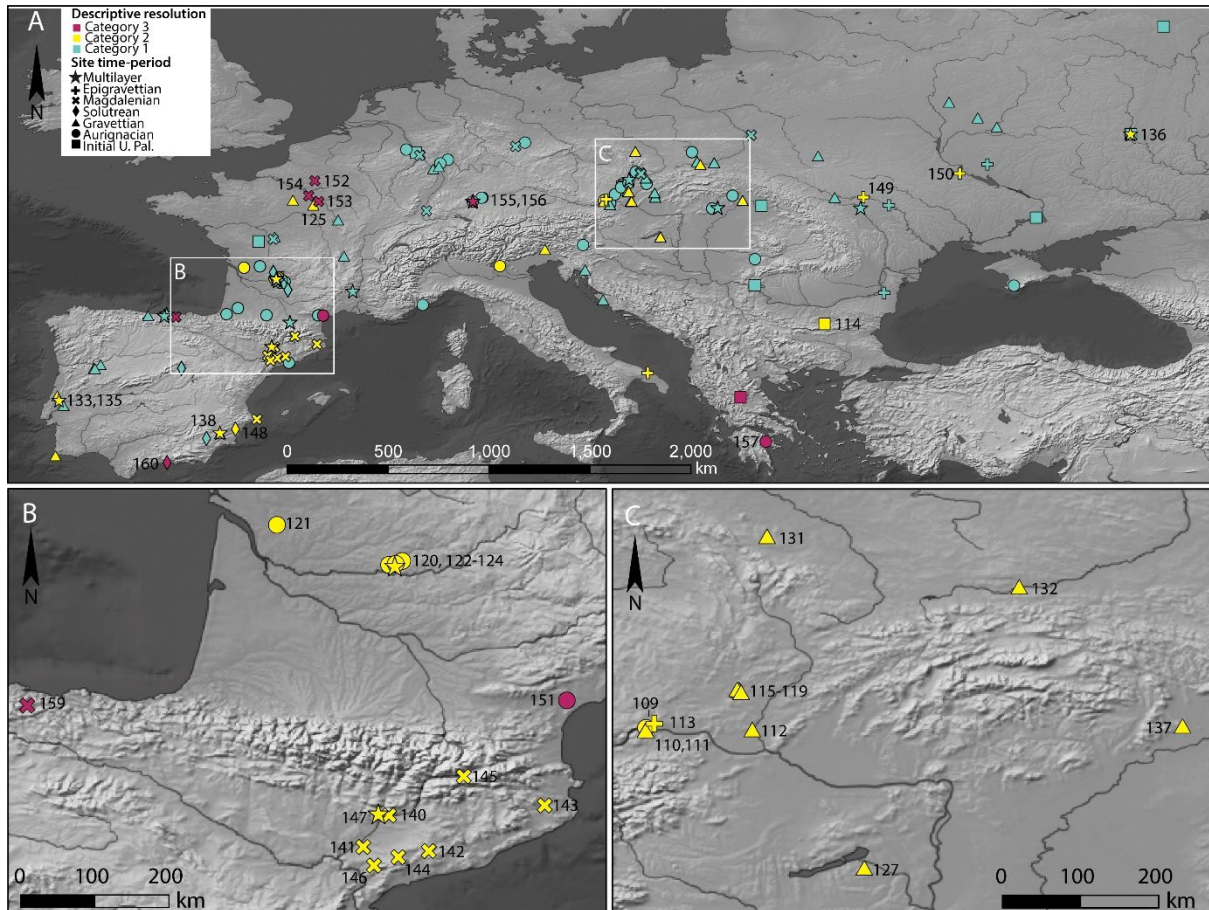


Figure 3: A) Map of all reviewed UP sites with described combustion features. Sites are categorised as 1 (blue), 2 (yellow) and 3 (purple) based on the published descriptive resolution available. Specific references for category 1 sites can be found in Table 1. Symbols indicate cultural associations. 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 ărie III, 137-Kostenki 14, 138- Šalitrena pećina, 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

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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.

Despite recent efforts (Goldberg & 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 are exceptionally rare and context specific.

With the currently available data, we can note that, while the early to middle UP are characterised 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

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3 sites) in the Périgord region of southern France and the Catalonia region of north-eastern Spain are shown in Figure 3 B. Most of Gravettian category 2 data comes from sites in the Middle Danube region of Central Europe (Figure 3 C) 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.

3.4.1 Variations in feature types during the UP

We were able to collect morphological information on 133 combustion features using field descriptions from categories 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 Figure 4. 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 (Figure 5). 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 to 18 ka cal BP. It was only in the late UP where we recovered data from several combustion features dated between 18 to 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.

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Figure 4: 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-Wachburg, 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 Figure 7), D) Clay lined prepared surface hearth – Klisoura Cave, Greece (Karkanas et al., 2004).

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

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several discrete overlapping lenses of intensely burned loam with charcoal (Hoffecker & Anikovich, 2014; Holliday et al., 2007; Sinitsyn, 2004). This Horizon of Hearths was dated by Optically Stimulated Luminescence (OSL) to between 47.8 – 40.1 ka BP (Hoffecker & 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 – 75 cm in diameter (Kozłowski, 1982) and date between 44.5-43.2 ka cal BP (Fewlass et al., 2020) (Recalibrated using Oxcal 4.4).

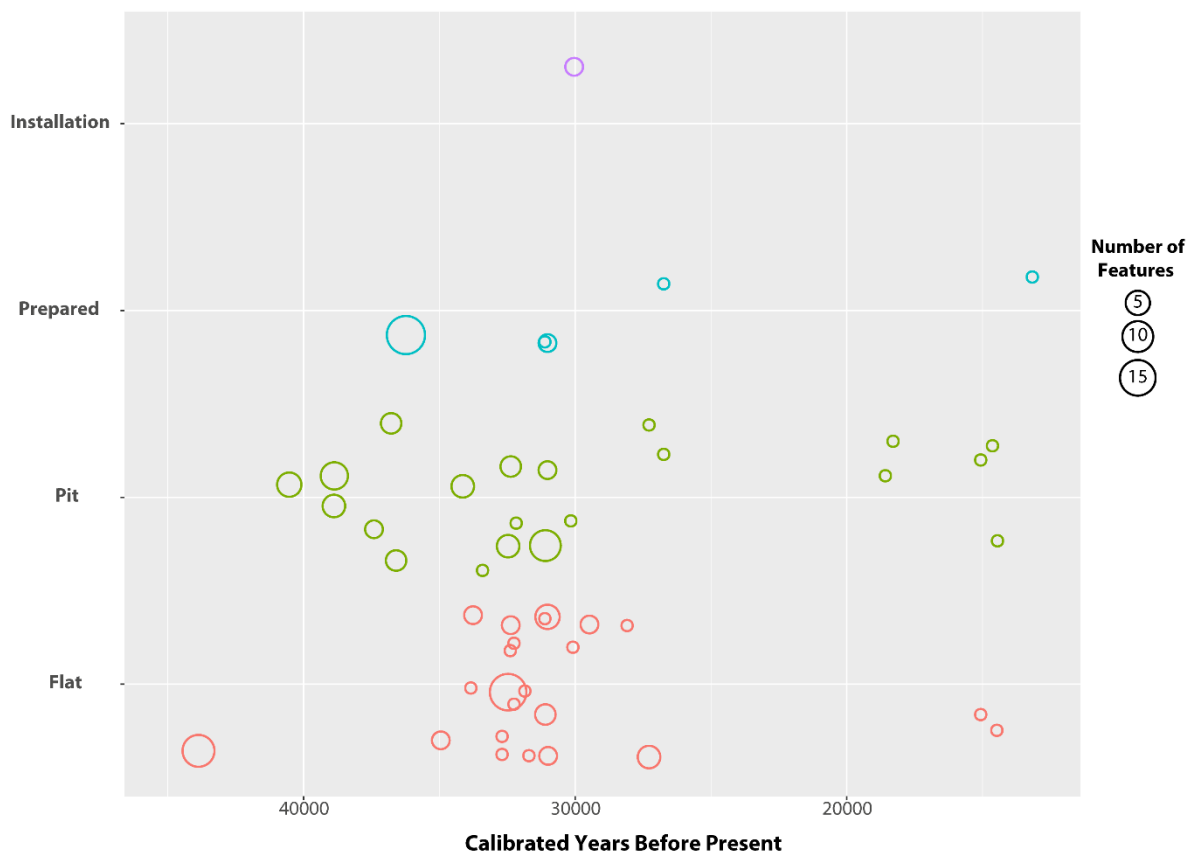


Figure 5: Temporal distribution of different contained combustion feature types per site and/or assemblage based on median calibrated years BP. Data was collected from individual combustion features described at Category 2 and 3 sites and was plotted using a jitter to avoid overplotting. Each bubble 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

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OxCal 4.4 using the InCal20 calibration curve with a probability 95.4% (Bronk Ramsey, 2009; Reimer et al., 2020).

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, 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 Regismont-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 90-25 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 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 suggest 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

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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, 2008b). 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, 2008b). 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, 2008b). Hearth B presented a 30 cm deep rubified (redden) substrate, which suggest prolonged or intensive use of this feature (Neugebauer-Maresch, 2008b). The other combustion features at this site were described as unlined flat hearths averaging 75 cm in diameter (Neugebauer-Maresch, 2008b). 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).

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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 & Henry, 2017; Mallol et al., 2013a; Mallol et al., 2013b). 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; Beresford-Jones et al., 2010; Svoboda et al., 2015; Svoboda et al., 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-Lutãrie III, a two phased hearth was described as having a high density of charcoal, calcined bone, ochre and burnt stone within the black layers (Anghelinu et al., 2020a). At the Magdalenian site of El Parco, in

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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 60-80 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 as well as 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

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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 Gran de 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).

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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; Svoboda et al., 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; Svoboda, 2013; Svoboda et al., 2013; Svoboda et al., 2016; Svoboda, 2007). 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 semi-circle 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 (Wattez, 1994) as a bowl-shaped structure filled with a mixture of bone, charcoals,

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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 10-20 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).

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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; Händel et al., 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 if these limestone blocks were incorporated into the structure as a burning basal surface or had another use (Svoboda, 2016). The ongoing excavations at Bistricioara-Lutãrie III in the Eastern Carpathian mountains uncovered another potential stone lined based of a hearth associated with the Late Gravettian layer 2.4 (Anghelinu et al., 2020a).

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In the late UP, there are examples of prepared surface hearths found on Iberian Solutrean and Magdalenian sites. A hearth from the Solutreo-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 Solutreo-Gravettian site of Ratila 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 combustions features are two "kiln like" hearths from Dolní Věstonice I (Svoboda et al., 2015; Svoboda et al., 2018; Vandiver et al., 1989). The two structures, found within residential units K2 and K3, were excavated by B. Klima in the 1950- 1970's (Svoboda et al.,

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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., 2003a) and from Aurignacian site of Regismont-le-Haut (Anderson et al., 2018). At both Hohles Fels and Geißenklösterle

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(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., 2003a). Micromorphological 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., 2003a). 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 artifacts, 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 artifacts during the UP (Medina-Alcaide et al., 2019; Medina-Alcaide et al., 2021; Medina-Alcaide et al., 2015)

3.5 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

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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 are, 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. Apart from the potential regionalised development of pyrotechnology, evidence for fire use in the EUP can still be characterised 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 to 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

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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 to the early UP (Figure 3). 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 & Davies, 2017; Simon et al., 2014; Svoboda et al., 2015; Vandiver et al., 1989; Verpoorte, 2000; Vlačiky 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 to 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 & Henry, 2017; Mallol et al., 2019a; Mallol et al., 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; Händel et al., 2015; Pryor et al., 2016; Simon et al., 2014; Svoboda et al., 2011; Svoboda et al., 2015). Our results show many Gravettian hearths surrounded by circular or semi-circular 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; Svoboda et al., 2016; Svoboda et al., 2018; Svoboda, 2016). While the exact function of these auxiliary structures

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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; Händel et al., 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.

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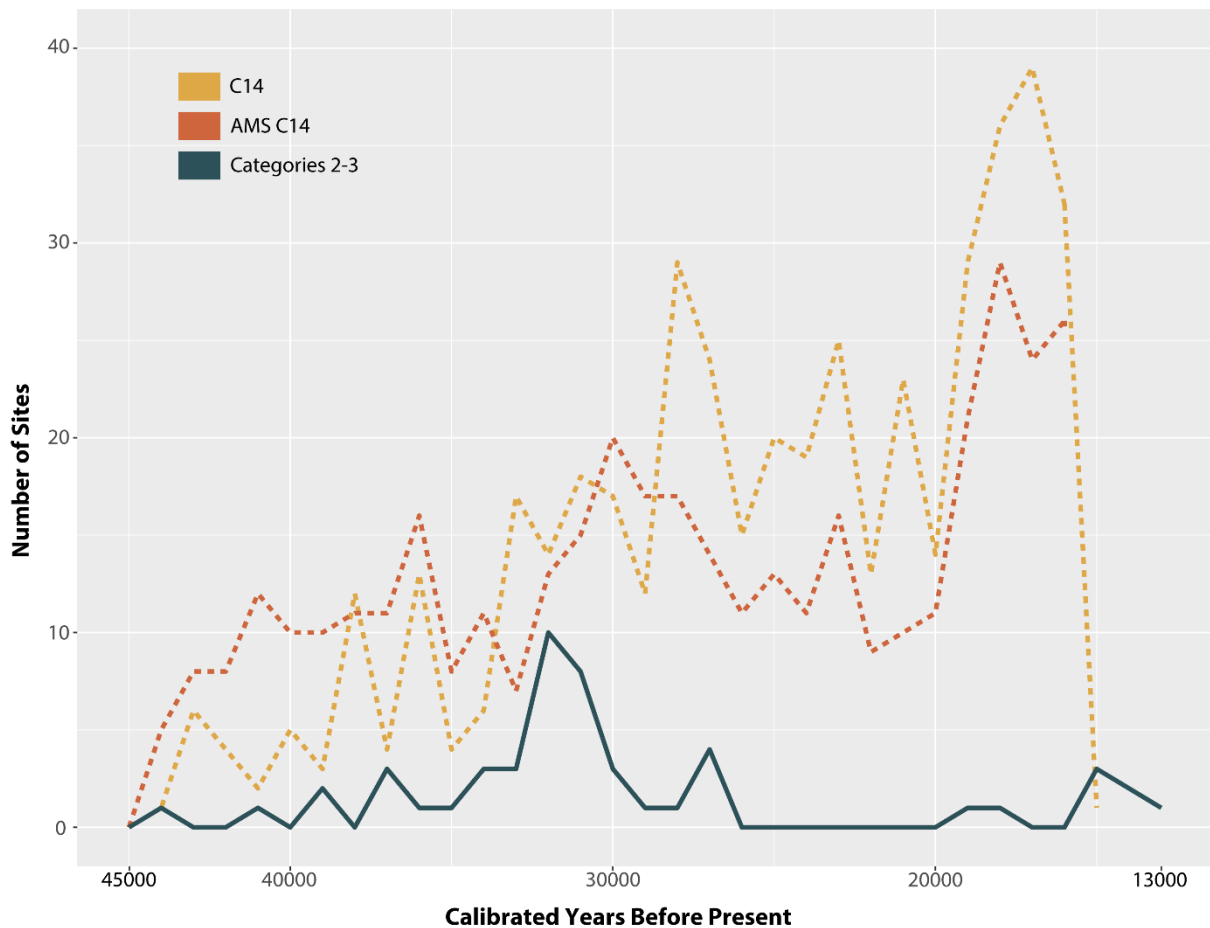


Figure 6: Comparison between the availability Category 2 and 3 site data compared to sites with C14 and AMS C14 dates within the Radiocarbon Palaeolithic Europe Database V28 (Vermeersch, 2020). The rectangle indicates the height of the Last Glacial Maximum (LGM) 26-19 ka BP. The median dates for Categories 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).

Surprisingly, however, our results show a clear gap of well described combustion features during the height of the LGM between 26-19 ka BP. Figure 6 shows the chronological distribution of our categories 2 and 3 data in comparison to UP sites with available radiometric and AMS C14 data within the Radiocarbon Palaeolithic Europe

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database V28 (Vermeersch, 2020). As this figure illustrates, while there is a decline in sites within the Radiocarbon database between ~28 to 19 ka cal BP, there are still substantially more UP sites during this period than the EUP between 48- 35 ka cal BP. Therefore, a lack of sites cannot be used to effectively explain the lack of well described combustion 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 colder environments (Henry, 2017; Pryor et al., 2016). LGM occupation sites with no evidence of fire use, i.e., with a demonstrated absence of

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combustion features or residues, could suggest different human groups had other behavioural adaptations 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., 2018b). 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 regionalised 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, show 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

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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; Marquer et al., 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 if 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, 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 if 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

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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.

3.4.1 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 if 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.

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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; if prior to firing or when the feature was already in use; or even if 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 & Henry, 2017) – see also the recorded variables used for this paper and detailed in the S.I. – Chapter 3. 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.

5.0 Conclusion

While much research has focused on when humans started to use fire and there has been a recent effort in understanding fire amongst 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 technocomplexes to better characterize the use of fire, and how such use changed amongst AMH in Europe. We collected data from published macro-observations and, when available, microstratigraphic and site formation data on combustion features, including dimensions, presence, thickness and nature of ash, charcoal, burned artifacts, 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 geographic 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 28-18 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 is 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

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features, such as pit or structured hearths, might be considerably overrepresented in published datasets when compared to – perceivably – simpler open flat hearths.

Overall, this review as highlighted the requirement for greater standardisation 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 standardisation 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.

Chapter 4

Fire use during the Last Glacial Maximum: evidence from the Epigravettian at Korman' 9, Middle Dniester Valley, Ukraine

Authors: William Chase Murphree^{1,*}, Cruz Ferro-Vázquez², Larissa Kulakovska³, Vitaly I. Usyk^{3,4}, Olesia Kononenko³, Marjolein D. Bosch^{5,6,7}, Paul Haesaerts⁸, Freddy Damblon⁸, Stéphane Pirson^{9,10}, Philip R. Nigst^{11,7,**}, Vera Aldeias^{1,**1}

Affiliations:

1) Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), University of Algarve (Portugal)

2) INCIPIIT-CSIC, Cidade da Cultura, Edificio Fontán, Santiago de Compostela, Spain

3) Institute of Archaeology, National Academy of Sciences of Ukraine, Kyiv, Ukraine

4) Institute of Archaeology, Czech Academy of Sciences, Brno, Czechia

5) Research Group Prehistoric Identities, Department of Prehistory and Western Asia and North African Archaeology, Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria

6) Turkana Basin Institute, Turkana, Kenya, & Turkana Basin Institute, Stony Brook University, New York, US

7) Human Evolution and Archaeological Sciences (HEAS), University of Vienna, Vienna, Austria

^{1*} Corresponding Author: William Chase Murphree, Email: wmurphree@ualg.pt

^{**} Co-Last Authors: Philip R. Nigst and Vera Aldeias

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8) Royal Belgian Institute of Natural Science, Brussels, Belgium

9) Agence wallonne du Patrimoine (AWaP), Service Public de Wallonie, Direction d'appui scientifique et technique, Jambes, Belgium

10) European Archaeometry Centre and Department of Geology, University of Liège, Belgium

11) Department of Prehistoric and Historical Archaeology, University of Vienna, Vienna, Austria

Abstract:

The Last Glacial maximum (LGM), spanning from 26.5 to 19 thousand years before present (ka BP), is a period of extreme climatic degradation associated with reduced biomass production and resource stress throughout Eurasia. Arguably, one of the most fundamental tools for human survival during this cold and arid period was the ability to create, maintain, and use fire. While fire is widely considered a ubiquitous tool in modern human behaviour, there are surprisingly few well-described combustion features during the LGM in Europe. In this paper, we provide high-resolution geoarchaeological research into three combustion features associated with Epigravettian occupations at the site of Korman'9 (Ukraine) with ages falling in the LGM. Our results show distinct variations in the size and structure of the combustion features, potentially indicating multiple occupations within the same layer or reflect differences in site organization or function during a single occupation. Additionally, our analysis shows clear evidence of the effect of solifluction and the lack of preservation of the ash layer(s) of the combustion features, as well as development of bioturbation features enhanced by anthropogenic input. To better estimate heating temperatures of the combustion events, we employed a novel approach

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using colour analysis showing temperatures reaching 600°C in the substrate underlying the combustion features. In all, the combustion features at Korman' 9 provide invaluable new insights as well as high resolution description of pyrotechnological behaviours during the LGM, which has been lacking during this critical period in our evolutionary history.

Keywords:

Fire use, Micromorphology, Colorimetric analysis, LGM, Upper Palaeolithic

4.1 Introduction

The Last Glacial Maximum (LGM) in Europe, roughly 26.5 through 19 thousand years before present (ka BP), corresponds to the latest period where the global volume of ice reached its maximum extent within the northern hemisphere (e.g., Hughes & Gibbard (2015); (Mix, 2001)). This period is characterized by rapid climatic deterioration, with extreme cold and arid conditions resulting in habitat loss and geographic isolation (e.g., Banks et al., 2008). These harsh climatic conditions are thought to have greatly impacted the distribution of Upper Palaeolithic anatomically modern human (AMH) populations and influenced both their behaviour and technology (Banks et al., 2008; Moreau et al., 2021). It's commonly hypothesised that populations were geographically isolated in so called refugia in the Balkans (Stiner et al., 2022) or Western Europe, including southern France and Iberia, where conditions were more favourable for both humans and animals (Straus, 2015). Whereas areas like the Middle Danube region of Central Europe show a clear decrease in population densities, with prevalence of spatially smaller and more widely scattered sites (Škrdla et al., 2021, p. 164). Moreover, from a lithic technological aspect, there is a clear trend for more regionalized named stone tool industries, such as the Solutrean in southwestern Europe and the Epigravettian in central, southern, southeastern and eastern Europe (e.g., (Banks et al., 2008; Hauck et al., 2017; Kulakovska et al., 2021; Nuzhnyi, 2006; Straus, 2015).

The LGM landscape in eastern Europe can be generally characterized by open and boreal steppe environments with numerous river systems flowing into the Black and Caspian Seas (Demidenko, 2021; Maier et al., 2023; Willis & Van Andel, 2004). The East European Plain is constrained by the Urals to the east and the Carpathian Mountains to

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the southwest. Many of the sites occupied during the LGM are located near the banks of the major river systems, with a significant number of known sites located on the Don (Russia), Prut (Romania and Ukraine), Dnieper and Dniester rivers in Ukraine and Moldova (Klein, 1973; Nigst et al., 2021; Noiret, 2009; Noiret et al., 2021; Noiret & Otte, 2010).

Similarly, to central Europe, Epigravettian occupations during the LGM appear to be ephemeral in nature with lower density of finds compared to the earlier Gravettian technocomplex (Anghelinu et al., 2020a; Demay et al., 2021; Demidenko, 2021; Škrdla et al., 2021).

It is widely assumed that a key tool for human survival, particularly during cold periods, is the ability to create, maintain, and use fire (Gilligan, 2010; Gowlett, 2006; Roebroeks & Villa, 2011; Sandgathe et al., 2011). A large body of literature has provided data on the benefits of fire use on hominin evolution and its fundamental function in everyday life (Aiello & Wheeler, 1995; Mallol & Henry, 2017; Roebroeks & Villa, 2011; Stahlschmidt et al., 2020; Wrangham, 2017). More recent papers on experimental and ethnographic research have also shown the labour-intensive nature of using pyrotechnology; meaning fire use is not only an essential survival tool but also played a key role in how hunter-gatherer populations organize themselves (Mallol & Henry, 2017; McCauley et al., 2020; Pryor et al., 2016). This includes: how hunter gatherers acquire resources like wooden fuels (Beresford-Jones et al., 2010; Pryor et al., 2016), if they stored or cached fuel materials for future use (Beresford-Jones et al., 2011; Pryor et al., 2016), how they started and maintained fires (Mallol & Henry, 2017; Mallol et al., 2007; McCauley et al., 2020), or how sites and activities are organized around combustion features (Clark et al., 2022; Galanidou, 1997; Rolland, 2004, 2018).

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While there are several ongoing debates on the prevalence of habitual fire use behaviour in early hominins (Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011; Stahlschmidt et al., 2015) or even in later European Middle Palaeolithic (Dibble et al., 2017; Dibble et al., 2018b; Sorensen et al., 2014; Sorensen, 2017), it is widely assumed that pyrotechnology was a ubiquitous behavioural adaptation during the Upper Palaeolithic (Chazan, 2017; Pryor et al., 2016). It is, therefore, surprising that in Chapter 3 (Murphree & Aldeias, 2022) – authored by some of us – on the available data on Upper Palaeolithic found an overall lack of well described combustion features during the LGM. We currently lack both macro- and micromorphological descriptions of fire features for this period beyond brief mentions of presence of features or combustion related residues (such as concentrations of charcoal, ash or indirect proxies of fire use like burned lithics). This scarcity of published data could be attributed to several factors, namely: either lack of preservation of fire remains during cold periods, a publication bias, or a potential lack of widespread fire use by modern humans during this period (Murphree & Aldeias, 2022). Concerning the latter possibility, we could consider that, with the onset of extreme cold conditions the lack of available wood fuel in steppe and grass land environments could have been an issue in which case human groups used other behavioural adaptations to survive, namely the consumption of rotten meat (Speth, 2017).

To address a possible gap of publications and preservation bias, we must better understand how we recognize and describe fire use in the archaeological record, both in the field and in subsequent reporting. Upper Palaeolithic combustion features vary significantly in terms of their structure: ranging from open flat hearths to potential kiln-like structures found at Upper Palaeolithic sites in Moravia (Mallol et al., 2017; Murphree & Aldeias, 2022; Svoboda et al., 2018). Based on the available descriptions of combustion

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features, it can be suggested that open flat hearths dominate the LGM and post-LGM landscape of Europe (Murphree & Aldeias, 2022). These simple flat combustion features are commonly comprised of three distinct strata: a reddish brown basal layer, followed by a black, organic-rich layer overlain by a white/grey layer (Aldeias et al., 2016; Goldberg et al., 2017; Mallol et al., 2013b; Mallol et al., 2017; Mentzer, 2014). A basal rubified layer can result from the thermal alteration of a substrate on top of which a hearth was built (Aldeias et al., 2016; Canti & Linford, 2000; Ferro-Vázquez et al., 2021; March et al., 2014). Whereas the presence of a black layer consists of burned material related to either the occupational surface on which the fire was built or fuel that was not fully combusted (Mallol et al., 2013a; Mallol et al., 2013b). In well-preserved features, the uppermost whitish layer is typically rich in ash and is the result of the complete combustion of wooden fuels (Braadbaart et al., 2012; Canti, 2003; Karkanas, 2021; Karkanas et al., 2002). These distinctions are important as much sedimentary features, like combustion features, are susceptible to syn- and post-depositional alterations. Combustion remains can easily be displaced by human actions (such as trampling or hearth rake out), whereas ashes can be dissolved or blown away by wind if left in an exposed surface (Goldberg et al., 2017; Miller et al., 2010; Schiegl et al., 2003a). As a result, the identification of fire features based solely on field observations is not always straightforward, which may have an implication on the lack of in-depth archaeological reporting of so-called simple flat combustion features. Moreover, as fire can be either natural or anthropogenic in origin, the distinction between the two can, at times, be problematic (Goldberg et al., 2017; Mentzer, 2014; Stahlschmidt et al., 2015). Generally, there is a clear need to better standardize the descriptions and consistently report combustion features in archaeology.

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In this paper, we present both macroscopic field-based descriptions and microstratigraphic analysis of three combustion features associated with Epigravettian occupations of Korman' 9, Ukraine. The combustion features were located in two separate archaeological layers (AL I and AL II) dating to around the height of the LGM, approx. 23-21 ka BP (Kulakovska et al., 2021). Macro-stratigraphic descriptions are based on the criteria outlined by Mallol et al. (2017) and Murphree and Aldeias (2022), while higher resolution analysis was conducted through employing soil micromorphological techniques, with descriptions following the nomenclature of Stoops (2003). We also provide a colorimetric analysis of the red layers for firing temperature estimation as proposed by Ferro-Vázquez et al. (2021). We then compare the results of our study in terms of similarities with neighbouring LGM sites. Finally, we discuss our results for understanding how combustion features and residues are preserved in periglacial conditions and their implications for understanding paleoenvironment, site organization, and fire use behaviours during the LGM in eastern Europe.

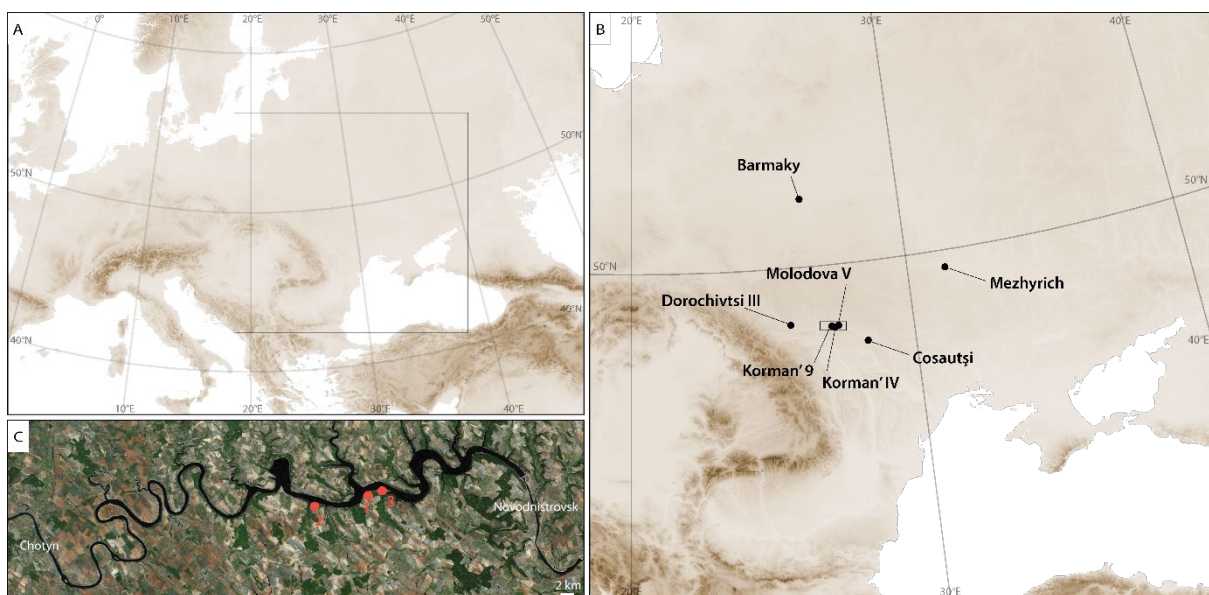


Figure 7: A) Map of Europe with the study area highlighted. B) Map of study area with key LGM and Post-LGM sites with described combustion features highlighted. C) Onset map of Middle Dniester valley with the LGM sites of Korman' 9 (1), Korman' IV (3), and Moldova V

(2) highlighted. Satellite image source: <https://worldwind.arc.nasa.gov>. Note the presence of a recent dam in C. Maps credit P.R. Nigst

4.2 Site setting, stratigraphy, and archaeological context

Korman' 9 is an Upper Palaeolithic site located on a northern facing slope on the right bank of the Dniester River in Ukraine (Kulakovska et al., 2021). The site is in the archaeologically rich Middle Dniester region, which features several nearby archaeological sites of similar chronologies, namely Doroschivitsi III, Korman' IV, Molodova I, and Molodova V (Chernysh, 1977, 1987; Klein, 1974; Kulakovska et al., 2021; Kulakovska et al., 2015; Noiret, 2009) – see Figure 7. Figure 7 (B) above also includes additional Ukrainian sites with later Epigravettian occupations like Barmaky and Mezhyrich (Chabai et al., 2022; Haesaerts et al., 2015; Hoffecker, 2005; Klein, 1974; Kulakovska et al., 2015; Marquer et al., 2012; Soffer et al., 1997). The Dniester River system is at the confluence of several waterways draining from the foothills of the Carpathians to the Black Sea. Within the section of the Middle Dniester valley, where Korman' 9 is located, the Dniester River has incised layers of Cretaceous rocks including argillites, sandstones, and limestones to the underlying protozoic stratum made up of siltstone, sandstones and argillites (Figure 8). The southern bank, where the site is located, is comprised of Miocene clay sandstones, siltstones, and conglomerates. Across the river, the northern bank consists of Miocene sands, gritstones, conglomerates, and tuffs. Currently this section of the Dniester is dammed and is part of a large reservoir lake, whose changing water table erodes the shoreline and banks intensely depending on the amount of yearly precipitation (Kulakovska et al., 2021).

The site of Korman' 9 was found in 2012 during a survey of sites along the Dniester River. Excavations started the following year as part of the Middle Dniester Palaeolithic

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project within the framework of the NEMO-ADAP project (Kulakovska et al., 2021). The site consists of ~ 50 m wide and roughly 4 m high cliff face incised into the southern slope of the valley (Kulakovska et al., 2021). A detailed overview of Korman' 9, including the site's stratigraphy, paleoenvironmental, and archaeological remains was published by Kulakovska et al. (2021). Here we will provide only a brief overview of the site's stratigraphy in direct relevance to the combustion features found at the site.

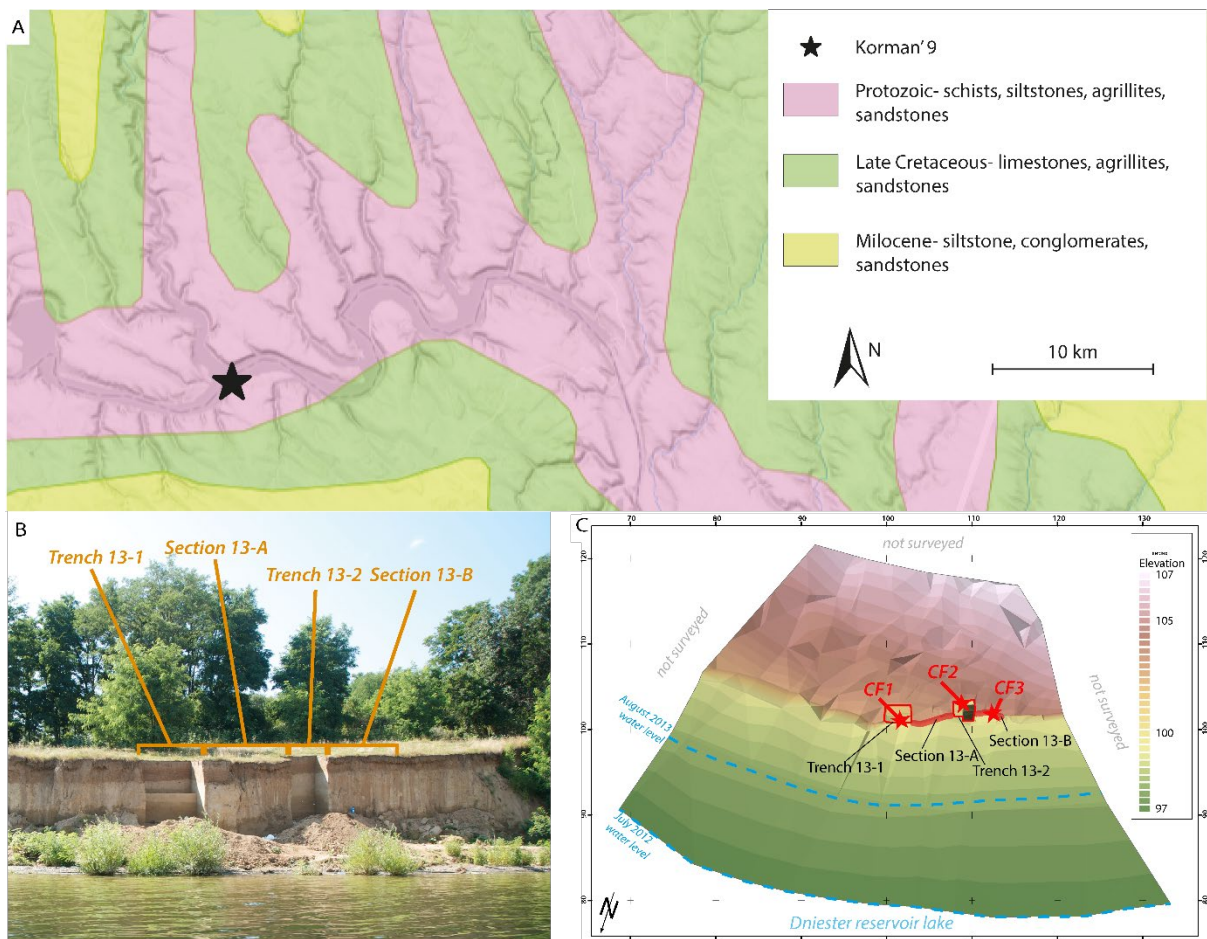


Figure 8: A) Geological map of the Middle Dniester Valley with Korman' 9 highlighted. Map source: Macrostrat (<https://macrostrat.org/map/loc/27.1893/48.5749#z=8.7>). B) site location on the Dniester River with the trenches and sections highlighted. C) digital elevation model for Korman'9 site. The locations of the combustion features are indicated by stars. Figure credit: W.C. Murphree & P.R. Nigst

The site's stratigraphic sequence is composed of aeolian silts and silty sand lithostratigraphic units capped by the Holocene illuviated horizon (Kulakovska et al.,

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2021). The sequence can be subdivided into five distinct lithostratigraphic units which were further subdivided into subunits (SU), described in Figure 4. Korman' 9 features four archaeological layers (AL), from top to bottom: AL 0, AL I, AL II, and AL III. AL I and II are associated with the Epigravettian and AL III with most likely Gravettian stone tool industries (Kulakovska et al., 2021). In total, three combustion features were discovered during the 2012 survey and the 2013 excavations at the site. Two of the combustion features, referred to henceforth as CF1 and CF2, were found within trenches 13-1 (CF1) and 13-2 (CF2) and are associated with AL I and the Epigravettian occupations at the site with an age between 22,167-21,398 cal BP (IntCal20, OxCal 4.4, 99.7% probability) (Kulakovska et al., 2021) – Figure 9. There is evidence of burning in both the lithic and fauna collections of AL I (Bosch et al., 2024; Kulakovska et al., 2021; Kulakovska et al., 2019). The third combustion feature, CF 3, was identified during cleaning of section 13-B and is associated with AL II, dated to between 22,645-22,086 cal BP (IntCal 20, OxCal 4.4, 99.7% probability) (Kulakovska et al., 2021). The dating of both AL I and AL II places the Epigravettian occupations at the middle of the LGM during both cold stadial conditions (AL II) and medium cold interstadial conditions (AL I) (Kulakovska et al., 2021, p. 248).

As outlined by Kulakovska et al. (2021), the archaeological work at the site followed state-of-the-art excavation methodology and techniques to collect high resolution lithostratigraphic provenience and piece plotting of artifacts. For the combustion feature CF1, several vertical sections were made to better observe the deposits in several cross-section profiles (Figures 11 and 12).

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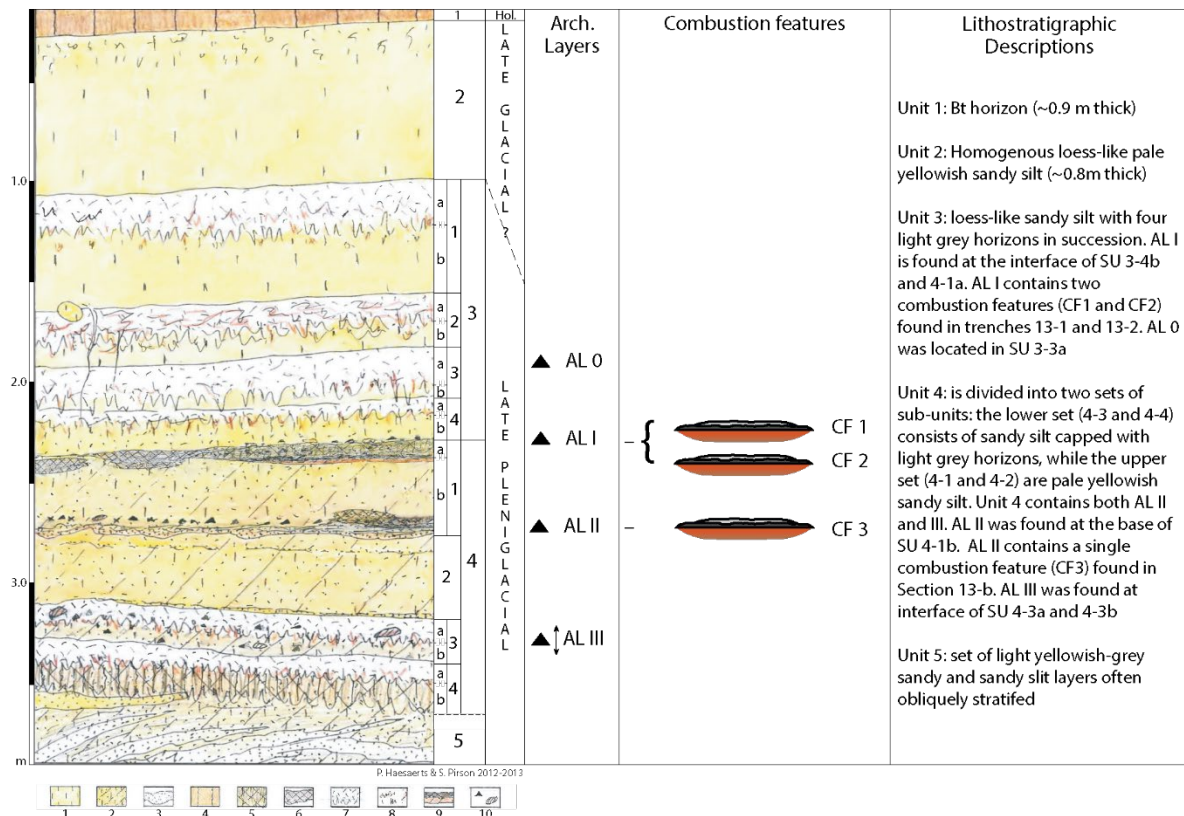


Figure 9: Lithostratigraphy of Korman' 9 with the location of the archaeological layers, combustion features and lithostratigraphic descriptions on the right. Figure credit: P.R. Nigst and W.C. Murphree, Stratigraphic drawing: P. Haesaerts and S. Pirson.

4.3 Methods

To describe and examine the combustion remains at Korman' 9, we employ a multiscale descriptive criterion for combustion features based on the methods used in Chapter 3. These include the following macro- and microstratigraphic descriptors: feature shape and dimensions; the presence and descriptions of ash (white layer), black (burned topsoil and charcoal), and red (rubified substrate) layers; the presence of superimposed layers or stacking; micro-observations such as the microstratigraphy of the combustion features and its contents as well as the degree of preservation of the combustion remains.

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For shape descriptions we employ the nomenclature for contained combustion features proposed by Mallol et al. (2017). The macro-observations of the combustion features at Korman' 9 were collected from field and excavation drawings, photographs, and field notes. We also created high resolution photogrammetry models utilizing the Agisoft Metashape program, version 1.7.5 (Agisoft, 2021) using photographs from the different phases of excavation of the features. The number of photographs varied based on availability for each section or excavation phase (see Table 1 in S.I.). The settings used in Agisoft Metashape for the model production and georeferencing are described in the S.I.

4.3.1 Soil Micromorphology

The micromorphological analysis is based on six micromorphological samples taken from CF1 and CF2 during the 2013 field season by one of us (PRN). In total, four samples were taken from CF1, labelled: Soil Micromorphology (SM)-01, SM-02, SM-04 and SM-05, along with a control sample SM-03 taken ~30 cm laterally to the west from samples SM-01 and SM-02 (Figure 11). A single sample (SM-09) was taken from CF2. Samples SM-01 and SM-04, as shown in the figures below, were fractured during transport from the Ukraine to the laboratory facilities at the Charles McBurney Laboratory for Geoarchaeology at the University of Cambridge (UK). The block samples were hardened using a standardized mixture of 1800 ml of crystic Polyester resin mixed with 200 ml of acetone and 1.0 ml of Methyl Ethyl Ketone catalyst (MEKP). The samples were then placed within a vacuum chamber to dry before thin section production. The resulting thin sections are 10 x 6.5 cm in size and are roughly 30 µm thick. Additional thin sections of blocks SM-04 and SM-05 were reproduced by Spectrum Petrographic (Vancouver, USA). The thin sections from Spectrum Petrographic are 7.5x 5 cm in size and 30 µm thick. All thin sections were

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scanned with an Epson flatbed scanner using 3200 dpi resolution and RGB photometric interpretation. The sections were then studied under a Nikon stereoscopic microscope (Eclipse SMZ25 / with camera Fi3Binocular) under magnifications from 0.5 to 200x and under a Nikon petrographic microscope (LV100ND with Ds/Ri2 Camera) at magnifications ranging from 20 to 400x in Plane-polarized and Cross-polarized light (PPL, XPL, respectively) at the Microscopy Laboratory "MICROLab" at Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), University of Algarve (Portugal). Micromorphological descriptions and nomenclature follow Stoops (2003).

4.3.2 Colorimetric analysis

We employed a method for thermal characterization of combustion remains using digital photographs. In a previous paper, Ferro-Vázquez et al. (2021), proposed a systematic method for the identification of archaeological heated sediments based on the instrumental measurement of colour in the CIELab system. This method consisted in the study of the colour of sediment samples heated under controlled conditions using a benchtop colorimeter to characterize the change in colour derived from mineralogical and physico-chemical transformations of the sediments when heated, leading to the production of haematite. Through discriminant analysis of colour data, the authors produced equations capable to accurately classify unknown samples as burnt or unburnt and, for those burnt, provided an estimation of the heating temperature to an accuracy that depended on the chemical and mineralogical composition of the sample (Ferro-Vázquez et al., 2021).

Here, we apply the methods and calculations from that study to digital photographs of CF1 (see detailed methods in S.I – Chapter 4) to obtain temperature

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estimations. Digital images contain large amounts of data, collected by means of simple, cheap, fast, and less laborious techniques than conventional soil and sediment analyses. The use of digital cameras (including built-in mobile phone cameras) has been proposed by various studies as soil-colour sensors (e.g., (Aydemir et al., 2004; Fan et al., 2017; Heil et al., 2020; O'Donnell et al., 2011; Rossel et al., 2008). The work from Levin et al. (2005) demonstrated that it is possible to obtain information on the chemical and physical properties of soils and sediments through the analysis of the colour of images taken with a standard digital camera in natural daylight, without any previous knowledge about the camera's characteristics, and with data acquisition and analysis based on commercially available software. Within the archaeological discipline, recent works by Haburaj et al. (2019) and Haburaj (2021) have used RGB colours from digital photographs for helping in the definition of stratigraphic layers, based on the correlation of RGB data with soil and sediment properties.

The photograph of CF1 was taken in late July 2013 in sunny weather conditions and $>30^{\circ}\text{C}$ temperature. The section was freshly cleaned and wet. At the time of photographing the north-facing section was in the shade. CF 1 (Figure 10 and 11) sits on SU 4-1a, which is assumed to be thermally modified producing a burned organic-rich black layer as well as an area of red-orange heated materials immediately below it corresponding to SU4-1b. Three sectors of the photograph assumed to be unheated, and representative of the average composition and weathering conditions of the site were selected as control (yellow circles), shown in Figure 4. In that regard, the parts of the photograph showing white colours were interpreted as concretions of Ca compounds. Such areas were avoided in the selection of the control locations since they were judged to not be representative, and since in this method we aim to characterize Fe oxide

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transformations upon heating rather than Ca related colour changes. A sequence of 5 points (red circles) at different distances of the combustion feature was also characterized, with the intention to capture the redder colours, thus the increase in temperature, in the sediment layers closer to the combustion feature (Figure 10). Two additional points (labelled ox) above the combustion feature (Figure 10) were sampled to test the capacity of the method for discriminating between reddish colours produced by temperature from those produced by weathering and reduction-oxidation processes.

Although the detailed analytical composition of the Korman'9 sediments is not available, it is known that they consist of loess type materials with variable amounts of Fe oxides and secondary Ca compounds. The latter are irregularly distributed throughout the profile (see Figure 4). Therefore, two of the seven compositional groups (CA) proposed in Ferro-Vázquez et al. (2021) were used for assessing the presence of heating and the temperature reached. The CA3 cluster corresponded to felsic silicate samples, with low Ca contents and moderate total Fe concentrations (1%–2%), with 30%–50% of the Fe in secondary. The CA6 consisted of samples from soils of calcareous composition that have different amounts of total Fe and Fe oxides but with high or very high amounts of Ca, and with most of their carbon being in inorganic pedogenetic forms.

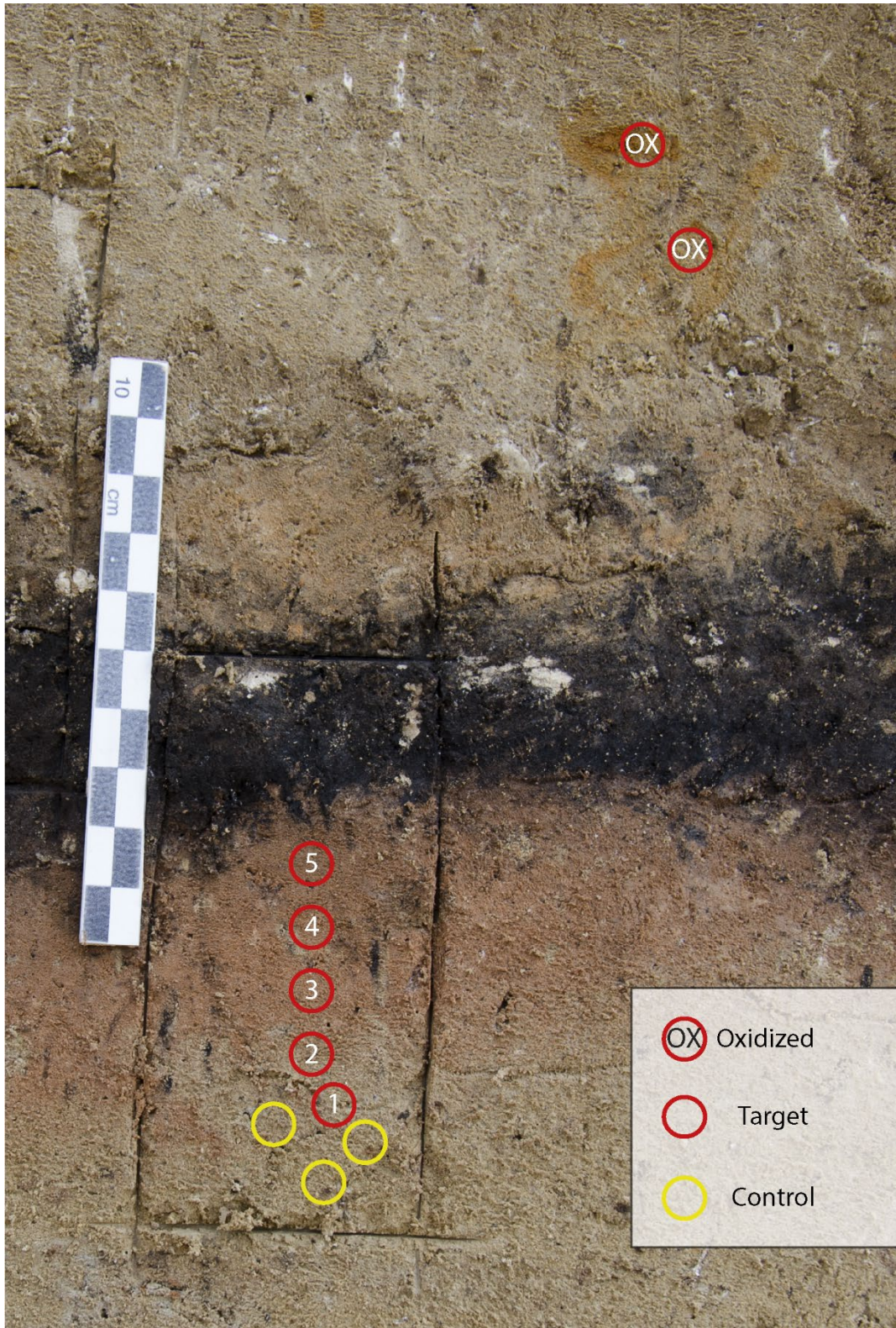


Figure 10: Colorimetric analysis for CF1. Location of the target (red circles), control (yellow), and oxidized sediments (OX) characterized in the analysis. Note the white mottles in the sediments corresponding to secondary Ca precipitates, and the orange colours, which correspond to higher amounts of Fe oxides.

4.4 Results

The results of our analysis for CF1 and CF2 are subdivided into macro- and micro-observations sections. Additionally, we present the results of colorimetric analysis for CF1 in the section below. CF3 was left unexcavated and only macro-stratigraphic descriptions are available.

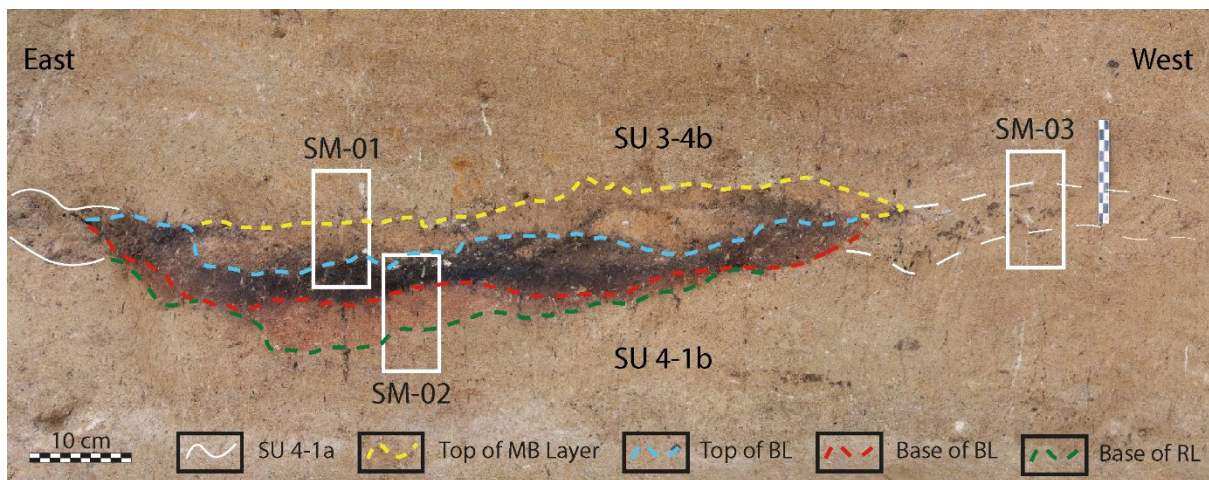


Figure 11: Korman'9, Trench 13-1, AL I, CF1: Annotated orthophotograph of the CF1 based on the Phase 0 model (cleaned section before excavation). Scale is 10 cm. The white boxes show the location for soil micromorphology samples (SM-01, SM-02, and SM-03). The extent of SU 4-1a is shown in the white lines. SU 4-1a becomes less visible further to the west as indicated by the dashed white lines. The four coloured dashed lines indicate the different contacts between the deposits of the combustion feature: yellow = top of the mottled brown (MB) deposit, light blue = top of the black layer (BL), red = the base of the BL, and the green indicates the base of the red layer (RL).

4.4.1 Combustion Feature 1

Macroscopic descriptions: CF1 is an unlined open flat combustion feature. The combustion feature is located at the surface of SU 4-1a, which consists of a highly bioturbated light brown silt exposed in excavation trench 13-1. Field observations, as well as paleoenvironmental markers (e.g., microfauna remains and sedimentary/pedogenic signatures) characterise SU 4-1a as a well-watered pedogenesis horizon associated with landscape stabilization during an interstadial event of sub-arctic cold conditions (see

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Kulakovska et al. (2021)). SU 4-1a becomes more diffused towards the west of the combustion feature. This SU overlies SU 4-1b and is below SU3-4b. Both SU 4-1b and SU3-4b consist of pale ochre yellowish loess-like sandy silt. Based on field observations by Kulakovska et al. (2021, p. 235), CF1 consists of three distinct deposits starting from the bottom to the top: a red layer (RL), a black layer (BL) and finally an overlying greyish or mottled brown (MB) deposit above (Figure 5). The RL has a maximum thickness of 4.6 cm and is approximately 70 cm in diameter. The BL has a maximum thickness of 4.4 cm and maximum extent of 1.0 m in length, based on measurements in Agisoft based on the model of the excavation phase 0 (Figure 11). Based on field observations, there is no clear evidence of superimposed combustion features or stacking (i.e., re-use of the same approximate location for several, discernible subsequent firing features). The undulating and convoluted nature of the deposits and their presence of a slope points to the effects of solifluction partially affecting the combustion feature deposits (Figure 12).

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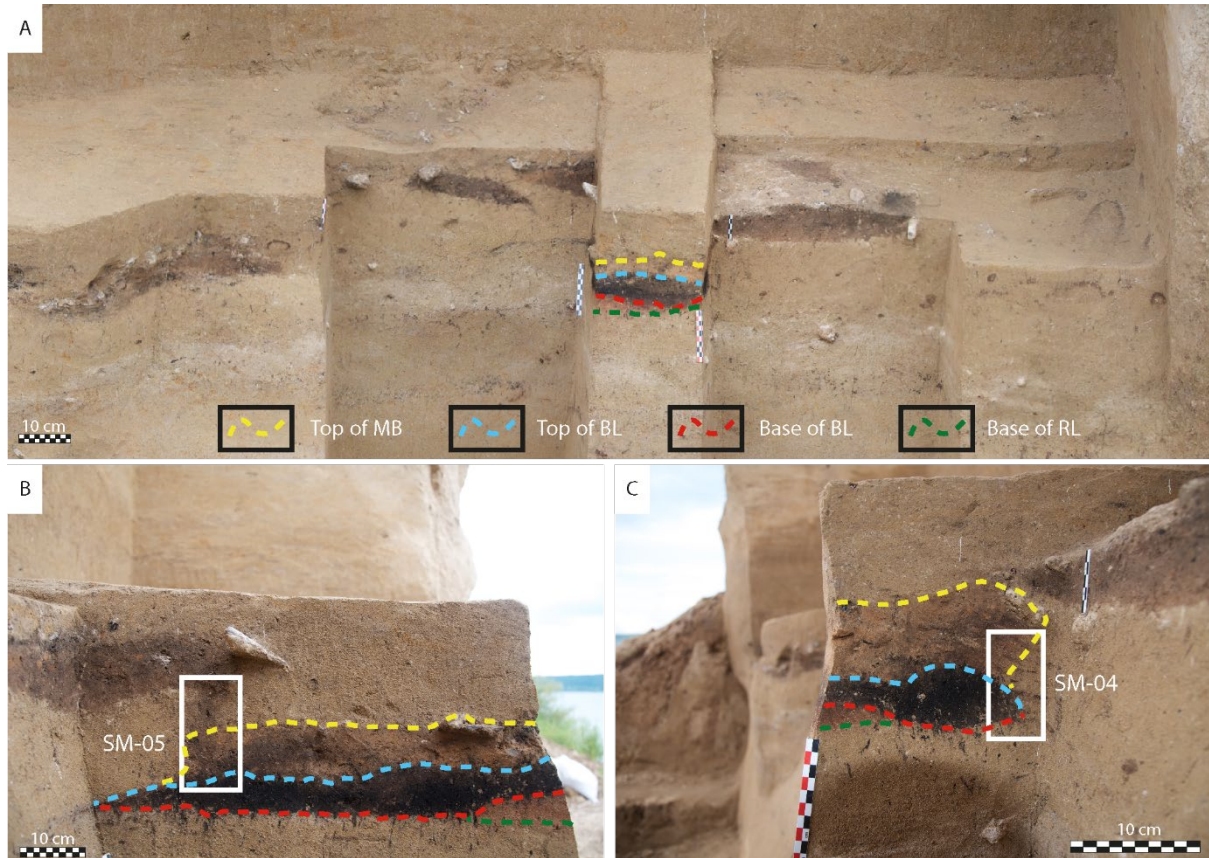


Figure 12: Korman' 9, Trench 13-1, AL I, CF1: A) Orthophotograph of CF1 model during Phase 3 of the excavation (after the removal of SM-01, SM-02 and SM-03 and exposure of new sections). The dark brown patches visible in the section are solifluction lobes. The two lower photographs show the left (B) and right (C) profiles of CF1. Model created by W.C. Murphree; photographs by P. R. Nigst. Scale in each photo is 10 cm. The white boxes indicate the sample location of micromorphology samples SM-05 (B) and SM-04 (C). The four dashed lines indicate the different deposits of the combustion feature: yellow= top of the mottled brown (MB) deposit, light blue = the top of the black layer (BL), red = the base of the BL, and green indicates the base of the red layer (RL).

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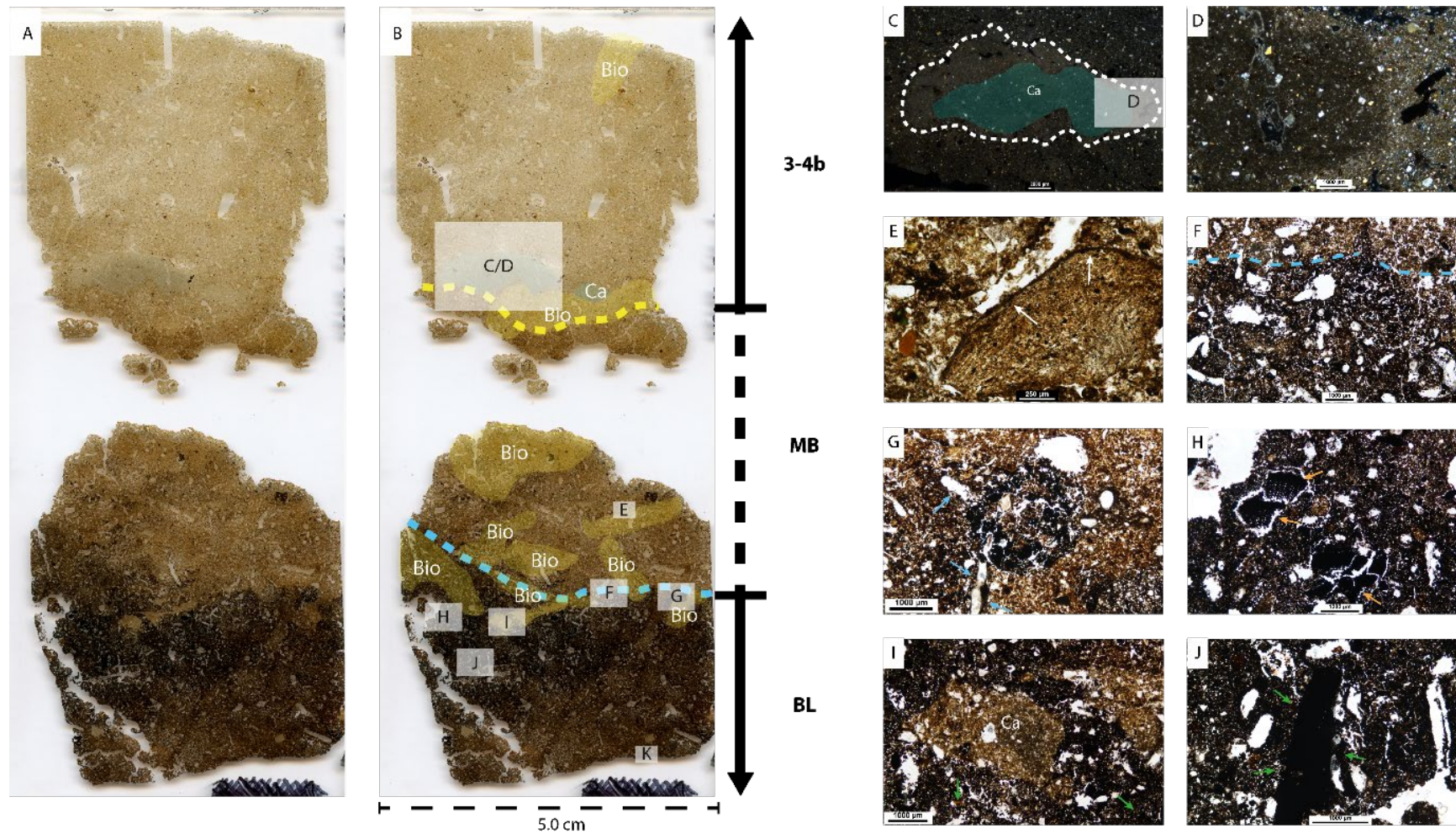


Figure 13: CF1 from Korman' 9, Trench 13-1, AL I: Thin sections and photomicrographs taken from SM-01 corresponding to CF1. A) the original thin section produced for SM-01. Note that the thin section was broken during transport prior to impregnation, hence the gap between the upper and lower deposits. B) Same thin section with the annotated contact of SU 3-4b, the MB deposit (yellow line), MB and BL (light blue line). Bioturbated (Bio) domains are highlighted in yellow, while calcium carbonate nodules (Ca) are highlighted in blue.

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Locations of photomicrograph are marked with the white transparent boxes. C) Calcium carbonate concretion or “Loess Dolls” (highlighted in blue and labelled Ca) with carbonates leaching into the surrounding sediment (extent indicated by the white dotted line) shown in cross-polarized light (XPL), scale is 2000 μm . D) Close up of the “loess doll” with carbonates leaching in the surrounding substrate, XPL, scale is 1000 μm . E) Capping (white arrows) on top of an aggregate within the MB deposit, Plane Polarized Light (PPL), scale is 250 μm . Cappings are common features in freeze-thaw related processes. F) Charred organic remains at the interface between MB and BL (blue line), PPL, scale is 1000 μm . G) Charred organic remains found within the MB/ BL contact, PPL, scale is 1000 μm . Note the common channels associated with bioturbation (blue arrows). H) Burned plant remains (light orange arrows) and spongy, very porous microstructure with abundant, vesicles, vughs, and channels found within the BL, PPL, scale is 1000 μm . The BL has abundant vesicles, channels, and highly interconnected vughs throughout the matrix. I) Calcium carbonate concretion (Ca) found within the BL, PPL, scale is 1000 μm . Note the lack of capping over the concretion. J) Fully carbonized bone (Stage 3 based on Stiner et al., 1995) within the BL, PPL, scale is 1000 μm .

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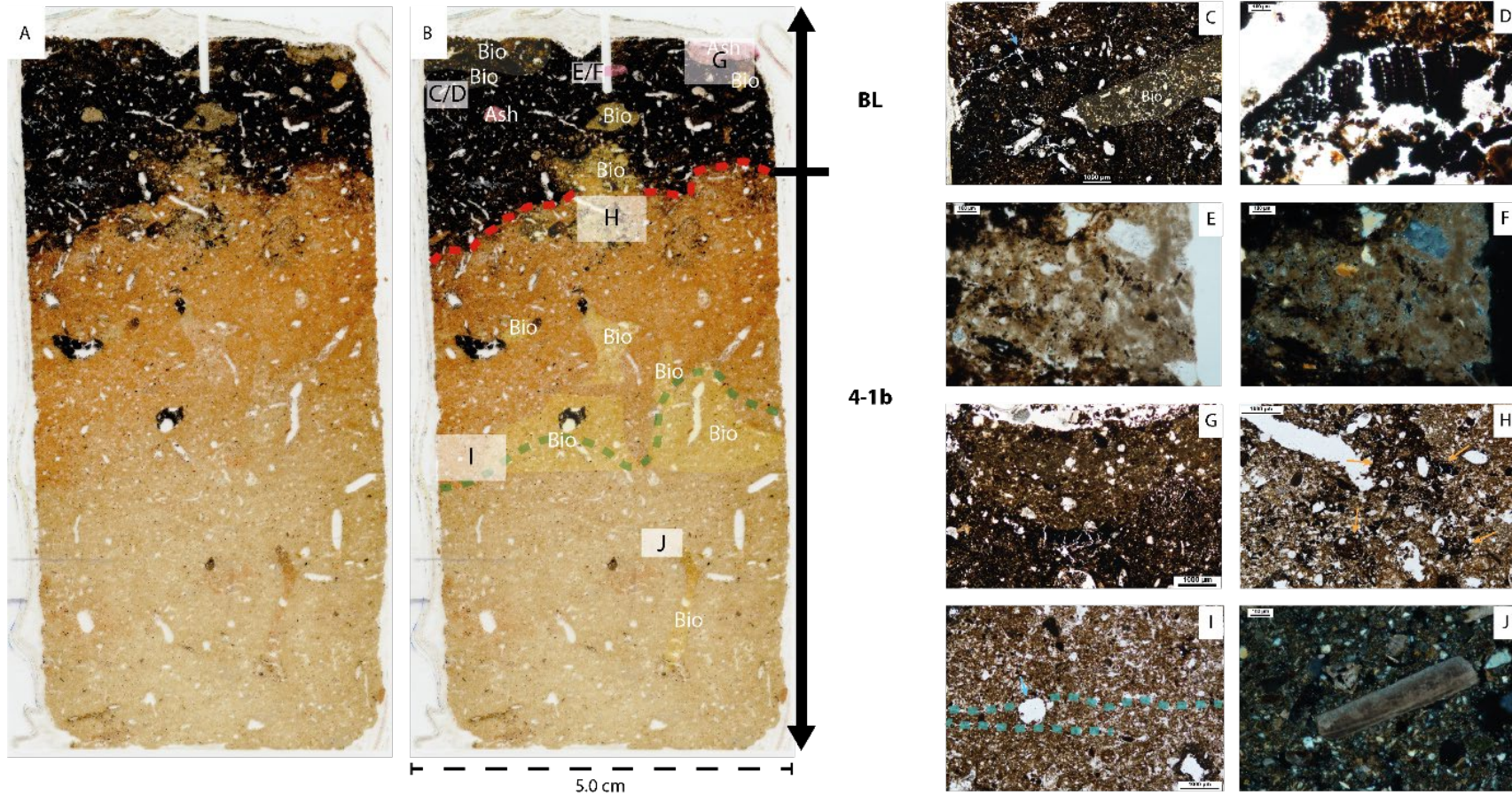


Figure 14: CF 1 from AL I in Trench 13-1: Thin sections and photomicrographs taken from SM-02. A) The original thin section scans produced for SM-02. B) Annotated thin section with the contacts between BL and RL (thermally altered SU 4-1b) (red line) overlying the unrubefied SU 4-1b sediments (green line). Bioturbated domains (Bio) are highlighted in yellow, and ash-rich domains (Ash) are highlighted in pink. Photomicrograph locations are shown in the white boxes. C) Photomicrograph of burned plant remains found within the BL, PPL, scale is 1000 µm. Some of which (blue arrow) appear to be broken via frost action. Vermicular structures from soil fauna burrowing are highlighted in yellow. D) Close up view of a charcoal shown in Figure 8-C, PPL, scale is 100 µm. Note that the remains appear to be humified and not fully

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carbonized. E) and F) Small isolated ash domain found within the BL, in PPL (E) and XPL (F), scale is 100 μm . G) Preserved ash domain within the BL, PPL, scale is 1000 μm . H) Burned plant and organic remains (orange arrows) mixed within the RL due to bioturbation, PPL, scale is 1000 μm . I) Weakly developed laminar/granular microstructures (light blue lines) and vesicles (blue arrow) associated with freeze-thaw affecting RL deposits, PPL scale is 1000 μm . J) Shell fragment within SU 4-1b, XPL, scale is 100 μm .

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Micromorphological descriptions (*samples SM-01, SM-02, SM-04, and SM-05*):

Based on observations from micromorphology samples SM-01 and SM-02 taken from Phase 0 of the excavation (Figure 11), CF1 consists of three distinct deposits with SU 3-4b above and SU 4-1b below. These deposits include, from bottom to top: a RL, a BL and a MB deposit. The matrix of the underlying unaltered SU 4-1b is a homogenous light yellowish brown well sorted silt with few, very fine, subangular sand-sized quartz grains, and few rounded glauconite grains. SU 4-1b has a generally massive microstructure with no separated peds and few voids (Stoops, 2003). The groundmass is calcitic crystallitic with some domains of mosaic speckled b-fabric, with generally regular vughs and chambers, some of which have hypocoatings of secondary carbonates associated with plant root casts (rhizoliths). The basal deposit of the combustion feature consists of the rubified thermally altered 4-1b called the RL. The RL (Figure 14) is a homogeneous reddish silt with fine sand-sized subangular quartz grains. RL has a weakly developed lenticular and vughy microstructure (Figure 14-I). The matrix contains of very few small, rounded mollusc shell fragments ~250 µm in size (Figure 14-J), as well as burnt plant remains directly associated with burrowing from soil fauna/flora (Figure 14-H). The contact between the unaltered and thermally altered 4-1b (RL) is diffused with no sharp contact. Near the contact between the RL and subunit 4-1b, the RL has a weakly developed platy/ granular structure (Figure 15-A) in comparison to subunit 4-1b, which has a generally massive microstructure. There is evidence of inverted grading between peds in subunit 4-1b (Figure 15-B) like what is described by Van Vliet-Lanoë (2010, p. 88) in similar sediments after the collapse of lenticular or platy microstructures

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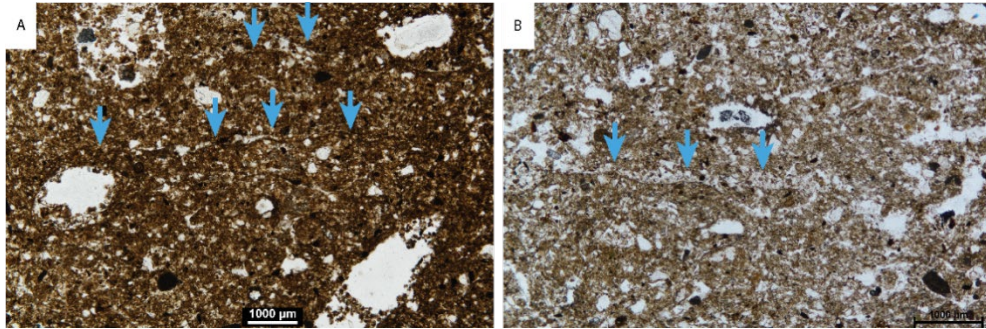


Figure 15: Photomicrographs from the RL and SU 4-1b in sample SM-02 showing the effects of cryoturbation. A) Domain of granulated microstructure within in RL deposit with cappings indicated by the blue arrows, PPL, scale is 1000. B) Inverse grading (blue arrows) where the underlying silt capping is covered with coarse grain materials potentially derived from collapsed lenticular microstructures

The RL has a sharp contact with the overlaying BL with localized bioturbation. The BL is a black, dense organic rich silt deposit with a spongy microstructure. The BL likely corresponds with thermally altered 4-1a. The deposit has abundant burned plant remains as well as few small, sand-sized burned bone fragments. These range from partially carbonized (stage 1 & 2), shown in Figure 13-I (green arrows), to fully carbonized (stage 3), shown in figure 7-J (green arrows), based on burning categories proposed by Stiner et al. (1995). The BL also has burned undefined minute organic material (Figure 14-G), and small (~1 mm sized) ash aggregates (Figure 14-E, 14-F, 14-G). No calcined bone was identified in the micromorphological samples SM-01 or SM-02. Some of the charcoal and plant remains are humified and/or partially burned (Figure 14-D). The upper deposit of the combustion feature consists of mottled brown (MB) fine-grained silt with fine grained sand-sized subangular quartz grains. The contact between the BL and overlying MB deposit is diffused with clear mixing at the contact between the two deposits. The MB deposit is organic-rich with a vughy microstructure, as well as some channels and domains of vermicular microstructure derived from soil fauna such as earthworm burrowing (Stoops, 2003). The matrix has small, rounded clay aggregates as well as very few cm-sized

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carbonate nodules. Some of the aggregates have clear capping (Figure 13-E). The contact between the MB deposit and SU 3-4b above is diffused (Figure 13). SU 3-4b has a similar composition to SU 4-1b except with the presence of very few small carbonate nodules (so called loess dolls), shown in figure 13-C and D. SU 3-4b has a generally massive microstructure with few voids. Overall, the two micromorphological samples associated with CF1, phase 0, show extensive bioturbation with localized mixing of the BL and RL of the combustion feature as well as between the RL and SU 4-1b sediments (Figures 13 and 14).

Micromorphological samples SM-04 and SM-05 were taken during the Phase 3 of the excavation of CF1 (Figure 12). Both deposits are affected by solifluction with clear overthrow. The RL is not present in either sample.

SM-04 consists primarily of the edge of the combustion feature (Figures 12 and 16). In this sample, the basal deposit, SU 4-1b has a generally massive microstructure with no separated peds and few void spaces. In this sample, there is a direct contact between SU 4-1b and MB layer which is diffused with mixing via bioturbation. There is a lens of the BL within the MB layer with a diffused lateral contact between the two deposits (Figure 16 A-D). The BL in sample SM-04 has a spongy microstructure with abundant channel voids and vermicular structures from soil fauna burrowing or plant roots. The deposit is organic rich with abundant burned and partially burned plant remains (Figure 16-H). On the upper slide (Figure 16 A and C) the MB deposit is deformed by solifluction there is a domain of irregular diffused contact with SU 3-4b. The MB deposit has a vughy microstructure with nonconnected vughs and chamber voids. This deposit contains rounded aggregates of SU 3-4b and rubified sediment.

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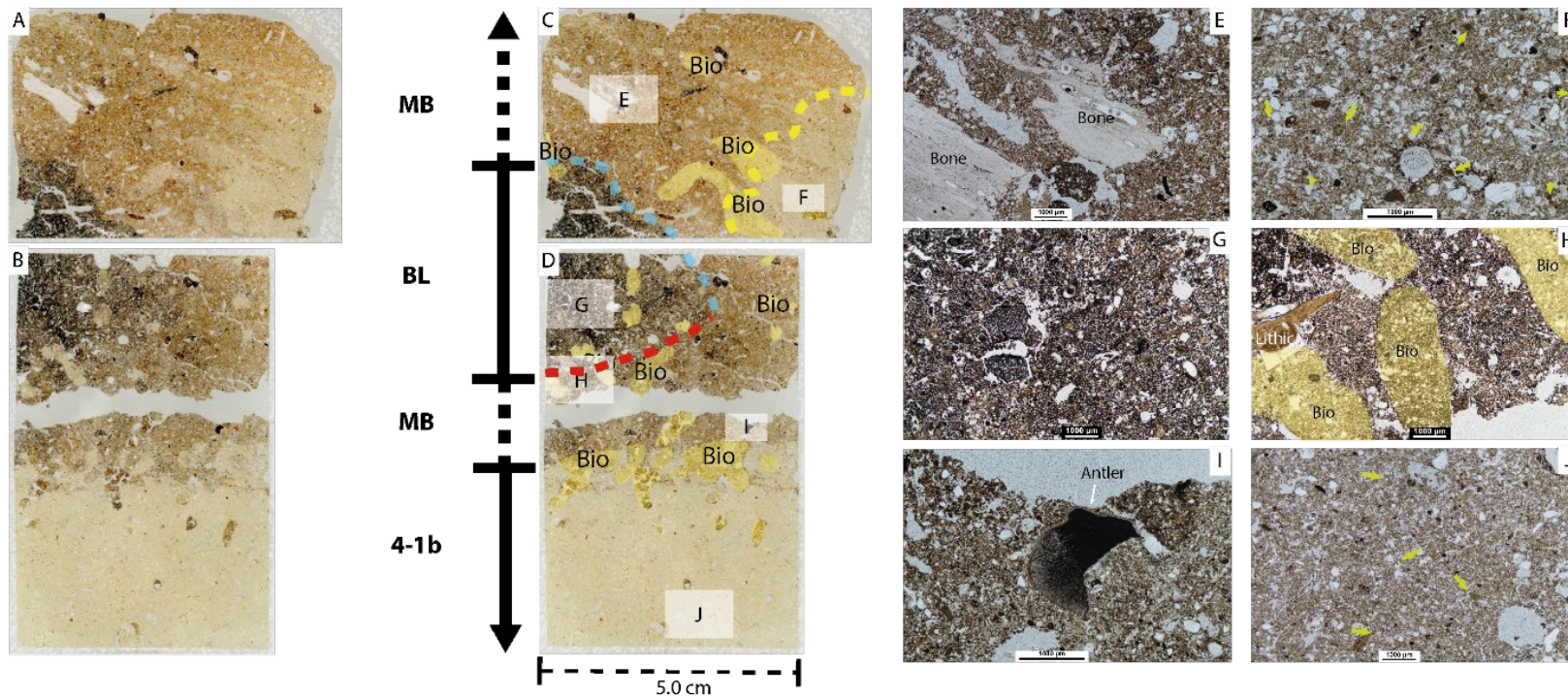


Figure 16: CF1, AL I, Trench 13-1: Thin sections and photomicrographs taken from sample SM-04. Sample location shown in Figure 7-C but further back into the section. Sections A) and B) are thin sections scans produced by Spectrum Petrographic. Sections C) and D) are the same image with annotations of the interfaces between MB and SU 3-4b deformed by solifluction (yellow line), MB and BL (light blue line) and RL (red line). Bioturbation (Bio) is highlighted in yellow, and the location of the photomicrographs shown to the right are indicated by the white boxes. E) Photomicrograph of unburned bones found within MB deposit (SU 4-1a), PPL, scale is 1000 μm . F) Photomicrograph of matrix of area marked in (c) showing of SU 3-4b showing moderately sorted with a common sand to fine sized quartz grains, massive microstructure with few void spaces, common silt-sized glauconite grains (yellow arrows) PPL, scale is 1000 μm . G) Spongy microstructure of BL with abundant charcoals, PPL, scale is 1000 μm . H) Partially burned lithic fragment within the MB deposit, bioturbation (highlighted in yellow) and contact with BL (demarked by the redline, PPL, scale is 1000 μm). I) Partially burned bone/antler found within the MB deposit near the interface with the underlying SU 4-1b, PPL, scale is 1000 μm . J) Well-sorted generally massive microstructure of the underlying SU 4-1b, PPL, scale is 1000 μm . Glauconite grains are marked by light green arrows

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The deposits sampled in SM-05 are again clearly affected by solifluction. The lower thin section shows a sharp contact with isolated mixing between the BL and the overlying SU 3-4b (Figure 17-B and D). The BL deposits have a generally spongy microstructure with clear evidence of bioturbation (Figure 17-D), containing both burned and unburned bone fragments as well as charcoal fragments (Figures 17-H). In the lower section, SU 3-4b has a generally massive microstructure with few channel voids and vughs. The upper thin section (figure 17-A and C) contains a diffused SU 3-4b with domains of MB. Here, SU 3-4b has a complex microstructure, which is generally massive with domains of vughs and channel voids (Figure 17-A and C). Some of the channel voids are infilled with microcrystalline carbonates or micrite (Figure 17-F). In the upper thin section, the diffused SU 3-4b deposit contains burned bone fragments, including one with an embedded lithic fragment (figure 17-I and J). The presence of an embedded flint flake in a bone clearly attests to human processing of this faunal remain. The mixing of anthropogenic materials (such as the burned bone with the embedded lithic) along with the isolated domains of MB deposits within the more geogenic deposits of SU 3-4b are likely derived from repeated solifluction events over time. The domains of MB materials are distinguishable due to colour and composition variations that derived from the relatively higher presence of sand-sized partially burned bone fragments (Figure 17-E) and charcoal remains.

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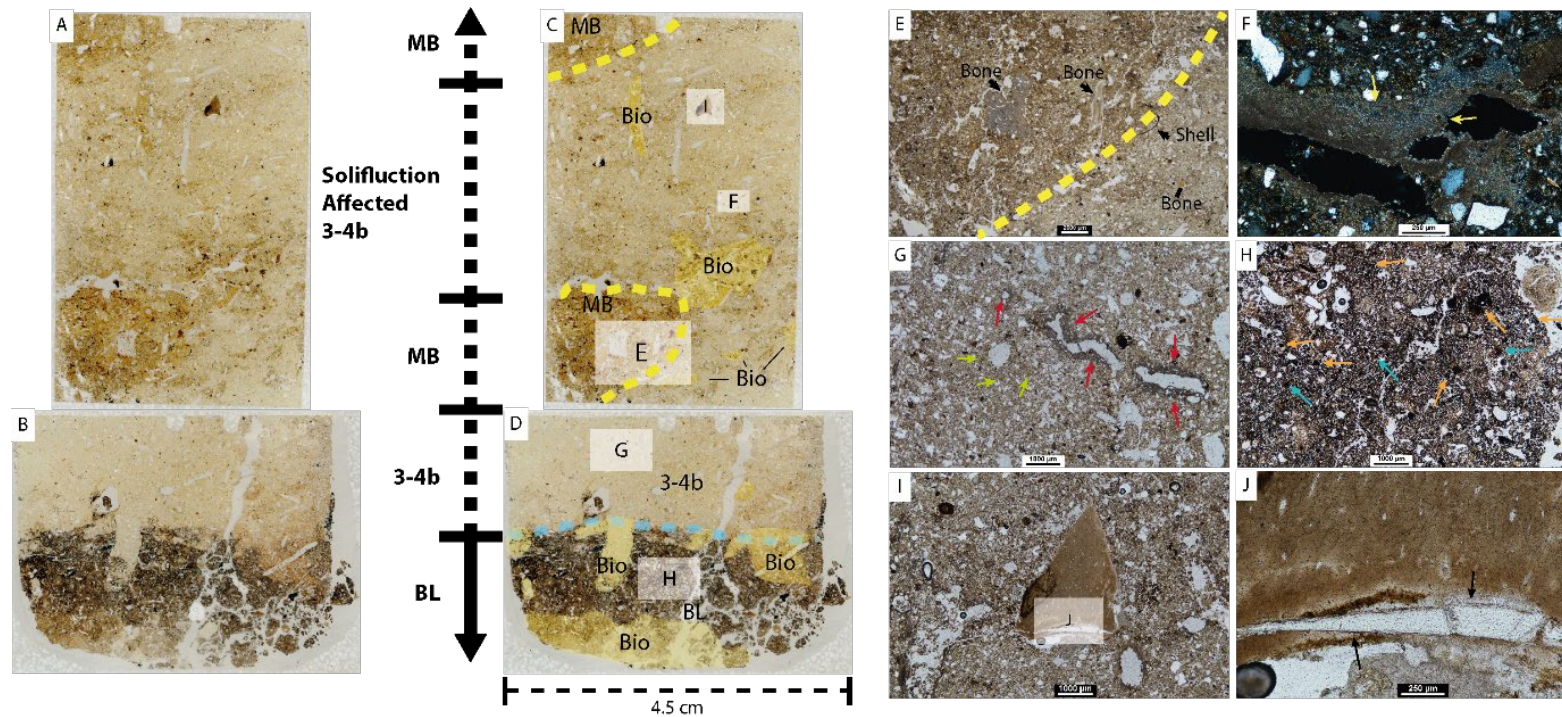


Figure 17: CF1 from AL I in Trench 13-1: Thin sections and photomicrographs from SM-05. A) and B) are thin sections scans produced by Spectrum Petrographic. Sections C) and D) are the same image with the annotated interfaces between MB and solifluction affected SU 3-4b (yellow line) and MB and BL (light blue line). Bioturbation (Bio) is highlighted in yellow, and the location of the photomicrographs shown below are indicated by the white boxes. E) Burned (calcined) and unburned bone fragments found near the interface between the MB and solifluction affected SU 3-4b (marked with the yellow line) in PPL, scale is 2000 μm . F) Secondary calcite (micrite) infilling (marked with yellow arrows) a channel void within the solifluction affected 3-4b, XPL, scale is 250 μm . G) Complex microstructure of SU 3-4b with few vesicles and channel voids with secondary calcite hypocoating (red arrows) and glauconite grains (light green arrows) PPL, scale is 1000 μm . H) Sand sized rounded burned organic remains/ charcoal (orange arrows), and sand-sized rounded bone fragments (blue arrows) within the BL, PPL, scale is 1000 μm . The BL has a generally spongy microstructure with vughs, vesicles, channel voids throughout the matrix. I) Lithic fragment embedded within a burned bone, PPL, scale is 1000 μm . J) Close up of the lithic fragment (black arrows) from (I), PPL, scale is 250 μm .

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Colorimetric analysis: The results of the colorimetric analysis of a digital photograph of CF1 used equations to assess if the sediments were heated, namely comparing the results to two sediment groups described in Ferro-Vázquez et al. (2021): CA6 (which considers sediment composition with high amounts of Ca) and CA3 (which corresponds to felsic silicates with low amounts of Ca). Applying both types of equations, the Korman' 9 sediments up to 5 cm below the BL of CF 1 were assigned as heated when compared with the control sediments (Figure 18 and see S.I.- Chapter 4 for data and calculations for CA6 equations). Then, we have chosen to use the equations of CA3 to further estimate to what temperatures these sediments might have been heated. This choice relies in the fact that, although Korman' 9 sediments have indeed certain amount of secondary Ca precipitates (consisted with CA6 type of sediments), such compounds are unevenly distributed as mottles and concretions (see white mottles in Figure 18) and are not the main components of the overall sedimentary matrix. In this regard, both the control and the target locations for CF1 colorimetric analysis were chosen avoiding white areas of the photograph, in a sampling strategy addressed to characterize Fe oxide transformations and not Ca related colour changes. The CA3 equations results show that, from 2-5 cm of distance from the BL, the sediments have been heated enough to produce mineralogical transformations and colour change. Temperatures of 200°C were reached at a distance of 5 cm (sample location 1, Figure 18-A), with temperatures of 500°C at 3 cm (sample location 3, Figure 12-A) and 600°C at 2 cm (sample location 4, Figure 19-A) (see S.I.- Chapter 4 for data and calculations). These results are consistent with previous experimental studies by Aldeias et al. (2016) on loess-like sediments, in which a temperature of 600°C at 2 cm of depth was reached after heating the sample at a temperature of 950°C during at least 3 hours. It is relevant to note that, in our calculations

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for the sediment at 1 cm below the BL (sample location 5, Figure 18-A), which would be the location expected to be heated at higher temperature given the proximity to the combustion event, results show a lower calculated temperature (approx. 300°C). However, it is clear that this part of the profile is stained with black organic particles from the BL deposit above it, which changes the values of L^* , a^* and b^* . Consequently, measurements at this location provide inaccurate temperature estimations and will thus not be considered for archaeological interpretations.

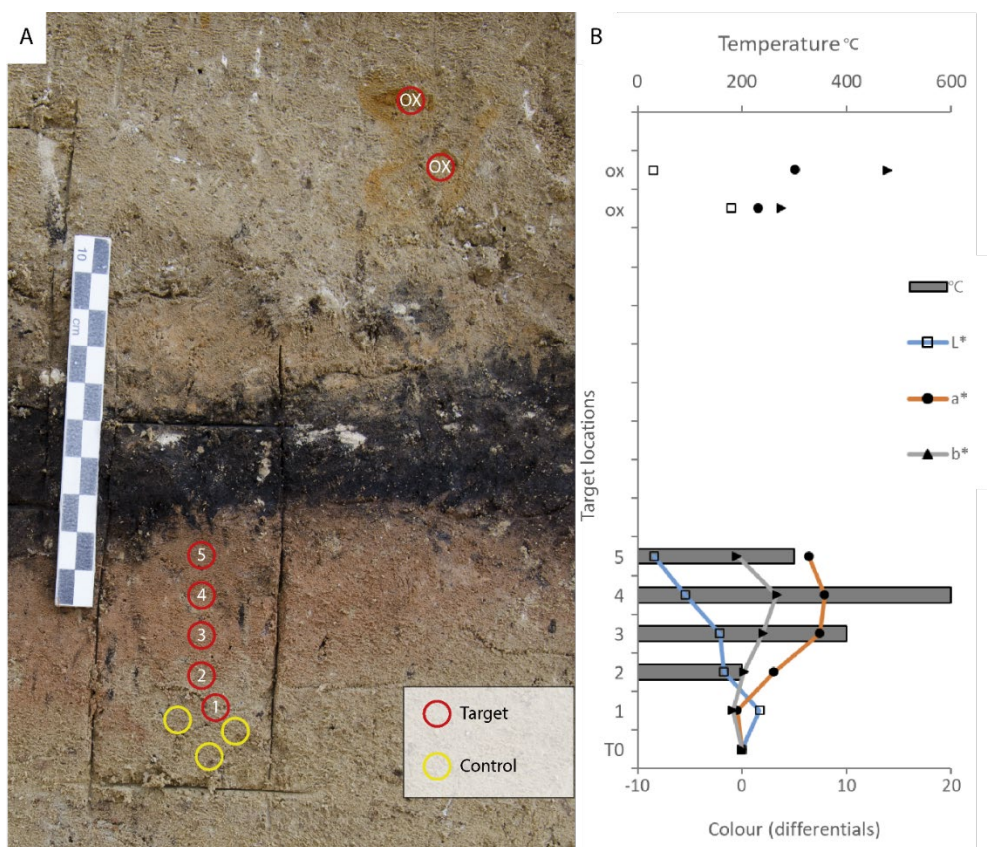


Figure 18: Colorimetric results for CF1. A) Location of the target (red circles), control (yellow), and oxidized sediments (OX) characterized in the analysis. B) Colorimetric analysis of the sample locations.

Micromorphological description of SM-03 – This sample was taken 30 cm to the west of phase 0 CF1 (Figure 11). The sample contains loessic materials from SU 3-4b and SU 4-1b with lenses of bioturbated SU 4-1a materials. The basal layer 4-1b is pale yellow

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homogenous well sorted silt, with a massive microstructure with some domains of weakly developed lenticular microstructures. 4-1b has very few vughs and channel voids some of which are infilled with secondary carbonates (Figure 19-G). The overlying SU 3-4b is a dense well sorted silt with lenses of bioturbated organic rich silt (likely 4-1a) as shown in Figures 19-B and C. The 3-4b has a complex microstructure with more granular microstructures near the interface with 4-1b as well as domains of weakly developed lenticular microstructures. The SU becomes more massive towards the top of the sample.

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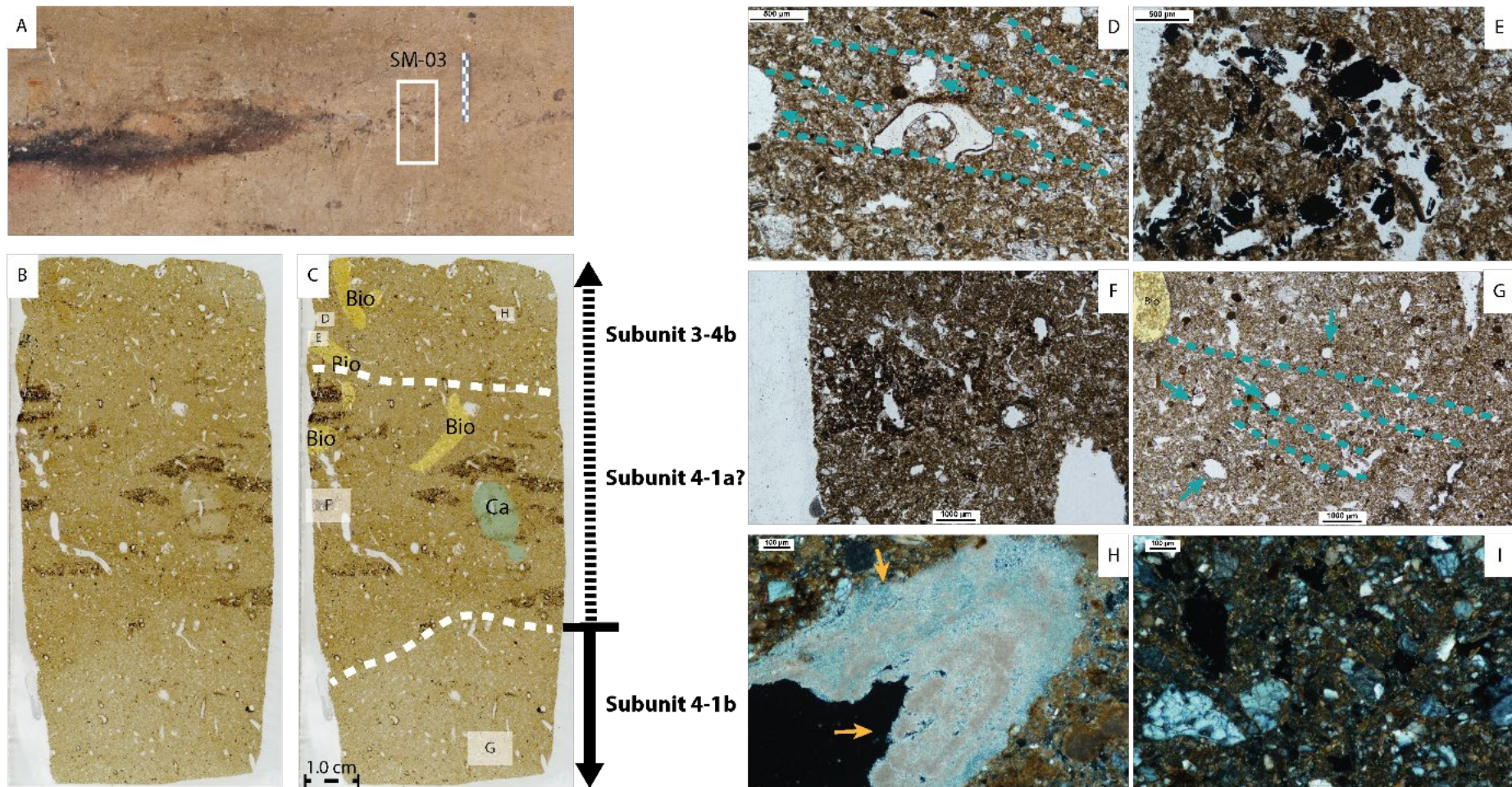


Figure 19:: Korman'9, Trench 13-1: Thin section scans and photomicrographs of SM-03. A) Orthophotograph of CF1 phase 0, showing the location of SM-03 just to the left of the CF1 deposits. B) Unaltered thin section scan. C) Annotated thin section scan of SM-03 with bioturbation (Bio) highlighted in yellow, Calcium carbonate nodule (Ca) shown in blue, and the locations of the photomicrograph indicated by the white boxes. At this sample location SU 4-1a only remains in small bioturbated lenses of sediments, as such it is difficult to delimit the

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extent of the unit. The diffused tentative limits of SU 4-1a are indicated by the white dashed lines. D-I) Photomicrographs from SM-03. D) Photomicrograph of unburned bone fragment found within SU 3-4b; PPL scale is 500 μm . SU 4-1a has a weakly developed laminar structure (light blue lines) and vesicles (blue arrow). E) Burned organic materials within a bioturbated section of SU 3-4b, PPL scale is 1000 μm . F) Bioturbated organic silt rich lens of SU 4-1a, PPL scale is 1000 μm . The lenses are more clay rich than the surrounding sediment of SU 3-4b, shown in photomicrograph (I), XPL scale is 100 μm . G) Weakly developed lenticular microstructure (light blue line) with vesicles (blue arrows) within SU 4-1b, PPL, scale is 1000 μm . SU 4-1b in this sample has complex microstructure, which is generally very dense and massive within the upper section of the sample then becomes more granular and platy nearer the base of the sample. In this photomicrograph, the microstructure is weakly developed laminar/platy with frequent vesicles, channels and vughs likely derived from freeze-thaw processes. H) Thick micritic infilling (orange arrows) of a channel void within SU 3-4b, XPL scale is 1000 μm . I) Close up view of the clay rich matrix of the organic lenses (SU 4-1a) from within Figure 16F, XPL, scale is 100 μm .

4.4.2 Combustion Feature 2

Macroscopic descriptions: CF2 is an unlined open flat combustion feature based on the nomenclature proposed by Mallol et al. (2017). The feature is located on top of SU 4-1a in excavation trench 13-2 (Figure 20), where it is affected by solifluction. The base of SU 4-1a has sharp contact with 4-1b. Above this contact there is max. 2-3 cm thick SU 4-1a with AL located on its top. CF2 is located at the same position. The overlying ~10 cm of sediment is a solifluction affected sequence of lenses of SU 4-1a interstratifying yellowish loessic sediment (either SU 4-1b or SU 3-4b). CF2 is roughly 82 cm in maximum diameter and roughly 3.5 cm in maximum thickness based on the model produced in Agisoft Metashape (Figure 20). However, the feature is likely deformed by solifluction. There is a thin ash layer, described by Kulakovska et al. (2021, p. 235) directly above the combustion feature, which overlays the BL and rubified (RL) layers that were clearly visible in the field. This layer likely corresponds to the MB layer described in the section below. Based on the model of CF2, the BL is 1.5 cm in maximum thickness while the RL is approximately 2 cm in maximum thickness. There is no visible evidence of stacking or superimposed combustion features.

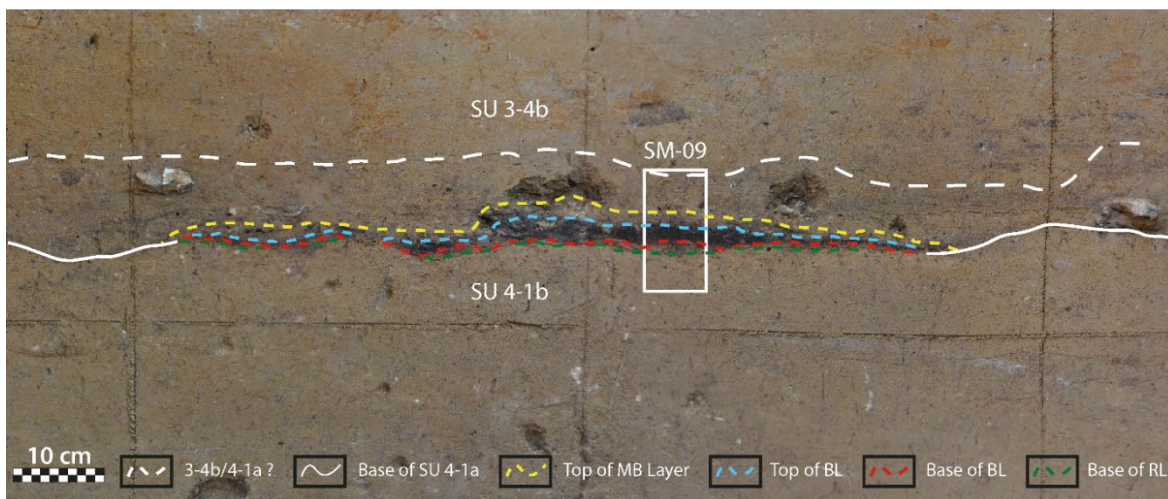


Figure 20: Korman' 9, Trench 13-2, AL I, CF2: Orthophotograph of the CF2. The white boxes show the location for soil micromorphology sample (SM-09). The four lines indicate the different interfaces between the combustion feature deposits: yellow= top of the MB deposit, light blue = the top of the BL, red = the base of the BL, and the green indicates the base of the RL. The solid white line delimits the contact between SU 4-1a and 4-1b. The dashed white line indicates the upper contact between 4-1a and 3-4b which is unclear with potentially several instances of solifluction and overlapping deposits. The boundaries between the two SUs are diffused with mixing throughout.

Micromorphological descriptions (*Sample SM-09*): CF2 has a single micromorphological sample SM-09 taken from trench 13-2 (Figure 20 and 21). SM-09 contains three distinct deposits related to the CF2: RL, BL, and MB (Figure 21). The section of SU 4-1b beneath CF2 has a complex microstructure with domains with no separated peds and few voids as well as domains of very weakly developed lenticular microstructure. This section of SU 4-1b is composed of dense homogenous, well sorted yellowish-brown silt with few fine sand-sized quartz grains and very fine sand-sized (~100 µm) rounded glauconite grains (Figure 21-F). Rhizoliths (root casts) and other secondary carbonate hypocoatings are impregnating the matrix around some of the void spaces. The contact between unburnt SU 4-1b and the overlying RL is relatively sharp but is interrupted by common bioturbation (Figure 21). The RL has a complex microstructure with domains of weakly developed granular and lenticular microstructures. The RL groundmass consists of a dense well sorted silt with few subangular sand-sized quartz grains (Figure 21-E). The contact between the BL and RL (SU 4-1b) is diffused with mixing due to bioturbation commonly found in both deposits (Figure 21). The BL is an organic rich silt (Figure 21-C and D). It has complex microstructure which is generally massive microstructure punctuated with few chambers, vughs, and vermicular structures as well as domains of very weakly developed lenticular structure. The deposits are composed of very few fine sand/silt-sized unidentifiable burned plant and organic remains (Figure 21-C). Above the

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BL is a thin lens of organically rich silt (MB) of which the organic content increases closer to the BL. In the upper portion of the thin section, there is the solifluction affected loessic sediment with patches of mixed SU 4-1a and 3-4b materials. This layer has a complex microstructure with common chamber voids and few vughs. Unlike the field observations, there is no identifiable ash preserved in the thin sections.

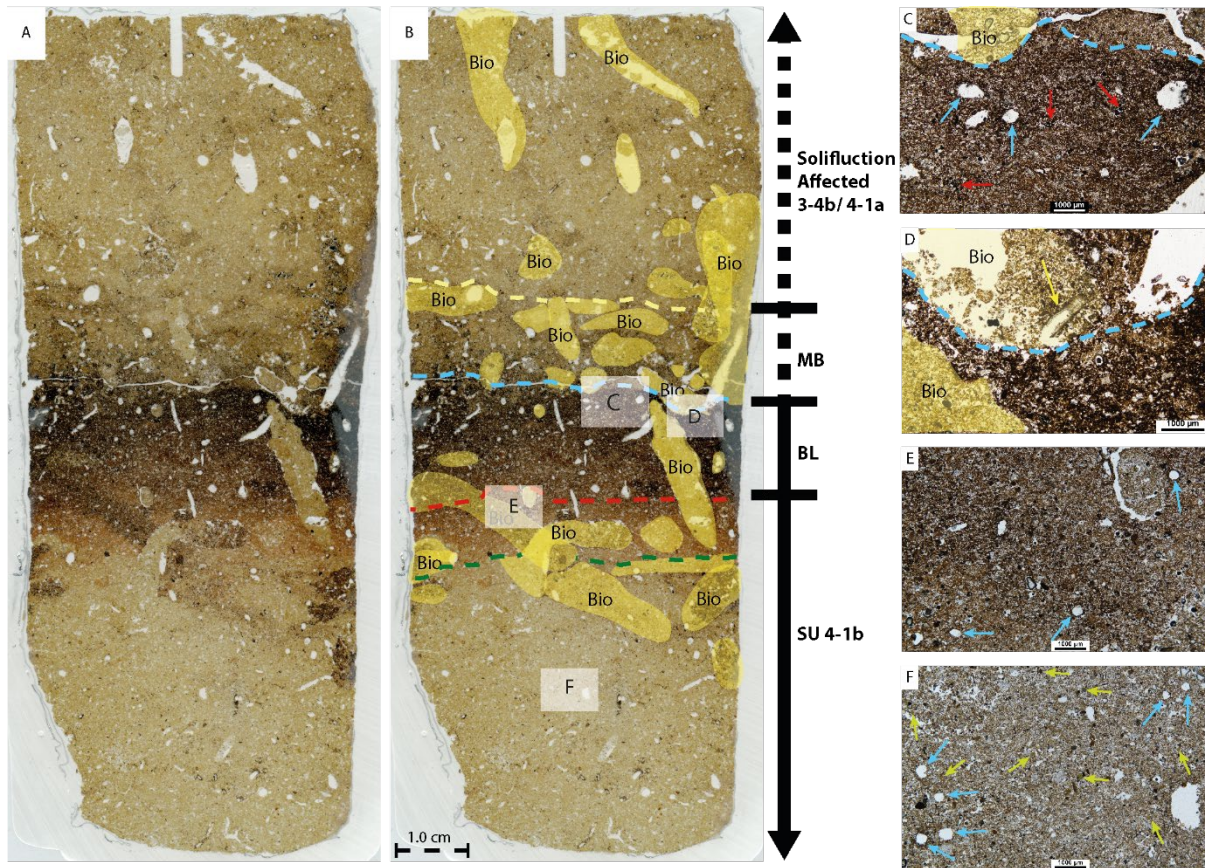


Figure 21: Korman' 9, Trench 13-2, AL I, CF2: SM-09 thin sections and photomicrographs. A) thin section scan of SM-09. B) thin section scan of SM-09 with the annotated interfaces between the solifluction affected SU 3-4b/4-1a deposit and top of MB (yellow line), top of BL (blue line) and top RL (red line) and contact between the base of RL (burned 4-1b) and unburned SU 4-1b (green line). Bioturbation (Bio) are highlighted in yellow. Photomicrograph locations are shown in the white boxes. C) Photomicrograph of dark organic BL sediments with vesicles (blue arrows). Burned plant remains are very rare within the BL, some of which are indicated by the red arrows. D) Root cast (yellow arrow) found at the interface of the BL and MB, PPL scale is 1000 μm . Yellow shaded regions indicate bioturbation. E) Dispersed organic matter mixing within the RL, PPL, scale is 1000 μm . The RL microstructure is generally well-sorted, massive with very few vesicles (blue arrows) and channels (due to bioturbation). F) unburned SU 4-1b underneath CF2, PPL, scale is 1000 μm . SU 4-1b has a massive microstructure with some vughs, vesicles (blue

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arrows) and rare vermicular structures resulting from the burrowing of soil microfauna. It also has common fine sand size glauconite (greenish yellow arrows) and quartz grains.

4.4.3 Combustion Feature 3

Macroscopic descriptions: CF3 is an unlined open flat combustion feature based on the nomenclature proposed by Mallol et al. (2017) (Figure 22). The CF3 structure is located within section 13-B. This structure was uncovered during cleaning of the exposed cliff (section 13-B) and was not fully excavated during the 2013 field season due to time constraints as it would have involved excavating >2.5m overlying sediments. CF3 is located in the lower part of SU 4-1b above a thin grey sand horizon (Kulakovska et al., 2021, p. 235). It is approximately 80 cm in diameter based on the photogrammetry model (Figure 22) using field photos. There is no clear evidence of an ash-rich (white) layer or mottle brown deposits visible from the macro-observations available. The BL is roughly 2-3 cm in maximum thickness, while the RL is approximately 2.6 cm in maximum thickness. There is no clear evidence of stacking or superimposed combustion features.



Figure 22: Korman'9, Section 13-B, AL II, CF3: View of the CF3 based on the model produced in Agisoft Metashape. The dashed lines indicate the various limits between the

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layers of CF3. The three lines indicate the different interfaces between the deposits of the combustion feature: light blue = the top of the BL, red = the base of the BL, and the green indicates the base of the RL. Model credit: W.C. Murphree.

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Table 2: Micromorphological sample ID and general micromorphological descriptions based on Stoops (2003)

Sample ID	Feature	Stratigraphic Subunit (SU)	C/F distribution	b-Fabric	Microstructure (MS)	Groundmass and Pedofeatures	Components
SM-01	CF1	<u>3-4b</u>	Open-Porphyr ic	<u>3-4b</u> -calcitic crystallitic and Mosaic	<u>3-4b</u> -Generally massive with weakly developed platy structure	<u>3-4b</u> - Homogenous dense well sorted silt with common subangular fine sand-sized quartz grains, calcite rich groundmass, frequent secondary calcific hypocoatings and rhizoliths	<u>3-4b</u> - few rounded glauconite, small cm-sized carbonate nodules, muscovite, subangular shell fragments
		<u>Brown Mottled layer (MB)</u>	Open-Porphyr ic	<u>MB</u> -calcitic crystallitic and Mosaic	<u>MB</u> - vughy with some domains of vermicular and weakly developed lenticular MS	<u>MB</u> - well sorted silt with common fine sand sized quartz, some organics, clear channels and bio galleries from soil fauna/flora, presence of cm-sized carbonate concretions, capping present on few aggregates;	<u>MB</u> - few 1 mm sized rounded clay aggregates, muscovite, frequent burned plant remains (associated with bioturbation);
		<u>Black layer (BL)</u>	Open-Porphyr ic	<u>BL</u> - undifferentiated	<u>BL</u> - vughy/ spongy MS	<u>BL</u> - dense, organic-rich silts with common fine sand size quartz grains, densely bioturbated with abundant channels and vermicular structures	<u>BL</u> - very dominant burned and partially burned plant remains, burned organic remains, and very few partially burned bone (stage 2 and 3).
SM-02	CF1	<u>BL</u>	Open-Porphyr ic	<u>BL</u> - undifferentiated	<u>BL</u> - vughy/ spongy MS	<u>BL</u> - dense organic rich silt with common fine sand-size quartz grains, densely bioturbated with abundant channels and vermicular structures	<u>BL</u> - very dominant burned and partially burned plant remains, burned organic remains, and rare partially burned bone (stage 2 and 3), very few fragments of ash lenses;
		<u>4-1b-RL</u>	Open-Porphyr ic	<u>RL</u> - generally calcitic crystallitic and mosaic	<u>RL</u> - Weakly developed lenticular/ granular	<u>RL</u> - Thermally altered dense well sorted silt with common fine sand size quartz	<u>RL</u> - few partially burned plant remains derived from bioturbation, very few thermally altered glauconite, few secondary carbonates infilling of void spaces

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Sample ID	Feature	Stratigraphic Subunit (SU)	C/F distribution	b-Fabric	Microstructure (MS)	Groundmass and Pedofeatures	Components
				with domains of granostriated			
		<u>4-1b</u>	Open-Porphyr ic	4-1b-calcitic crystallitic	<u>4-1b</u> - generally massive with domains of weakly developed platy/ granular MS near RL interface.	<u>4-1b</u> - Homogenous dense well sorted silt with common subangular fine sand sized quartz grains, capping present on some aggregates	<u>4-1b</u> - few glauconite grains, rhizoliths, secondary CaCO ₃ infilling.
SM-04	CF1	<u>MB</u>	Open-Porphyr ic	<u>MB</u> -speckled and calcitic crystallitic.	<u>MB</u> - generally massive MS	<u>MB</u> - well sorted silt with common fine sand sized quartz, some organics, clear channels and bio galleries from soil fauna/flora, Diffused interface with 3-4b	<u>MB</u> - few rounded Glauconite, small cm sized carbonate nodules, few unburned bone fragments very few silex fragments, antler fragment, rhizoliths, and secondary CaCO ₃ infilling
		<u>BL</u>	Open-Porphyr ic	<u>BL</u> - undifferentiated	<u>BL</u> - vughy / spongy MS	<u>BL</u> - dense organic rich silt with common fine sand-size quartz grains, densely bioturbated with abundant channels and vermicular structures	<u>BL</u> – dominant burned and partially burned plant remains
		<u>4-1b</u>	Open-Porphyr ic	<u>4-1b</u> - speckled and calcitic crystallitic.	<u>4-1b</u> -generally massive MS	<u>4-1b</u> - homogenous dense well sorted silt with common fine sand sized subangular quartz grains, few vughs without hypocoatings	<u>4-1b</u> - few rounded Glauconite, small cm sized carbonate nodules, muscovite, few subangular shell fragments; very few silex fragments;
SM-05	CF1	<u>Solifluction affected 3-4b</u>	Open-Porphyr ic	<u>3-4b</u> - speckled and calcitic crystallitic;	<u>3-4b</u> – Complex MS	<u>3-4b</u> - Mottled, dense, well sorted silt with common fine sand sized subangular quartz grains, some vughs w/o hypocoatings, 3-4b becomes more homogenous closer to BL layer	<u>3-4b</u> – few glauconite grains, rhizoliths, secondary CaCO ₃ infilling, Bone fragment with embedded silex, rare charcoal fragment

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Sample ID	Feature	Stratigraphic Subunit (SU)	C/F distribution	b-Fabric	Microstructure (MS)	Groundmass and Pedofeatures	Components
		<u>MB</u>	Open-Porphyr ic	<u>MB</u> - speckled and calcitic crystalline;	<u>MB</u> - Complex MS	<u>MB</u> -well sorted silt with common fine sand sized quartz, some organics	<u>MB</u> - few rounded Glauconite, small cm sized carbonate nodules, few unburned bone fragments
		<u>BL</u>	Open-Porphyr ic	<u>BL</u> - undifferentiated	<u>BL</u> - vuggy/ spongy MS	<u>BL</u> - organic rich silt with common fine sand size quartz grains, densely bioturbated with common channels and vermicular structures	BL – dominant burned and partially burned plant remains
SM-09	CF2	<u>Solifluction affected 3-4b/4-1a</u>	Open-Porphyr ic	<u>3-4b</u> - speckled;	<u>3-4b</u> - Massive MS with domains of very weakly developed lenticular MS	<u>3-4b</u> - Mottled, dense, well sorted silt with common fine sand size quartz grains, calcite rich;	<u>3-4b</u> – few glauconite grains, rhizoliths, secondary CaCO ₃ infilling
		<u>MB</u>	Open-Porphyr ic	MB- speckled;	<u>MB</u> -Generally massive MS	<u>MB</u> - well sorted silt with common fine sand sized quartz, some organics, bioturbated with mixing of material from underlying BL	<u>MB</u> - rare burned and partially burned plant remains
		<u>BL</u>	Open-Porphyr ic	<u>BL</u> – undifferentiated;	<u>BL</u> - generally massive with domains of weakly developed lenticular MS	<u>BL</u> – dense organic rich silt, densely bioturbated	<u>BL</u> – very few burned and partially burned plant remains
		<u>4-1b- RL</u>	Open-Porphyr ic	<u>RL</u> - undifferentiated	<u>RL</u> -generally massive MS with domains of very weakly developed lenticular MS	<u>RL</u> – Thermally altered dense well sorted silt with common fine sand-size quartz grains,	RL- very few partially burned plant remains derived from bioturbation, very few thermally altered glauconite, few secondary carbonate infilling of void spaces
		<u>4-1b</u>	Open-Porphyr ic	<u>4-1b</u> - speckled;	<u>4-1b</u> - Generally massive MS with domains of very weakly developed	<u>4-1b</u> - homogenous, dense, well sorted silt with common fine sand size quartz grains, calcite rich	<u>4-1b</u> - few rounded glauconite, very few shell fragments, very few burned plant remains

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Sample ID	Feature	Stratigraphic Subunit (SU)	C/F distribution	b-Fabric	Microstructure (MS)	Groundmass and Pedofeatures	Components
					lenticular MS		
SM-03	Control sample about 30 cm west of CF1	<u>3-4b</u>	Open-Porphyr ic	<u>3-4b</u> - speckled clays and calcitic crystallitic	<u>3-4b</u> – complex MS. Granulated MS at the base with a more massive MS towards the upper portion of the section, domains of lenticular MS	3-4b – dense well sorted silt with common fine sand sized quartz, some lenses of more organic silt (4-1a).	<u>3-4b</u> – few glauconite grains, rhizoliths, secondary CaCO ₃ infilling, very few sand sized bone fragments
		<u>4-1b</u>	Open-Porphyr ic	<u>4-1b</u> - speckled clays and calcitic crystallitic	<u>4-1b</u> -Generally massive MS with some domains of weakly developed lenticular MS	<u>4-1b</u> - homogenous, dense well sorted silt with common fine sand sized quartz	<u>4-1b</u> – few glauconite grains, rhizoliths, secondary CaCO ₃ infilling

4.5 Discussion

Given the lack of in-depth reports on fire use during the LGM (Murphree & Aldeias, 2022), it is of interest to better characterize any evidence we have related to combustion behaviours from this period. The combination of both macroscopic and in-depth micromorphological analysis from the site of Korman' 9 allows us to better characterize the types of features used by Upper Paleolithic communities at the site, as well as the degree of preservation associated with fire use in open air sites such as Korman' 9. As stated in the section above, CF3 was unexcavated, so our conclusions on site formation and fire related behaviours are limited to the combustion features CF1 and CF2, associated with AL I.

4.5.1 Combustion residues:

CF1 – Based on the field data and macro-observations, CF1 is an open flat hearth. There is no indications of stone linings or associated features around the combustion feature. The ash component of CF1 is poorly preserved with only isolated domains and small aggregates of recrystallized ash identified in thin section (Figure 14-E and F). The plant remains within the BL consist of small organic fragments, some (though not all) of which present some red hues indicative that the materials are not fully combusted. This organic-rich composition combined with the considerable thickness and extension of the BL sediments – around 4.4 cm and maximum extent of 1.0 m – tends to support the conclusion by Mallol et al. (2013b) that the black layer represents, at least to some extent, the burned topsoil of an exposed surface. However, The BL also has some anthropogenic input marked by the presence of isolated ash aggregates, rounded sand sized burned

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bone, and charcoal in the BL is likely due to the intensive bioturbation from soil fauna after the abandonment of the feature. There was only one fragment of partially calcined bone visible in an isolated domain of the MB, shown in Figure 17-E. Most of the bone fragments found within the BL and MB of CF1 are only partially carbonized (below ~600°C), suggesting the bone fragments were not directly exposed to high temperatures associated with a flaming fire (Stiner et al., 1995) (See also: Bosch et al., 2024; Bosch et al., 2012; Gallo et al., 2021; Théry-Parisot, 2002; Théry-Parisot et al., 2005). However, it is possible that the presence of unidentified burned organic remains (potentially char or burned animal fats) within the MB and mixed within the BL of CF1 is due to subsistence practices (Bosch et al., 2024). Based on our observations of lack of calcined spongy bone and common charcoal fragments, we can conclude that wood, not bone is the primary fuel source for CF1. Although we cannot exclude the use of dung or fats as fuels at this stage of analysis. The scarcity of larger charcoal fragments within the thin sections makes it difficult to determine which type of wood was the primary fuel source, though the anthracological analysis of the available macroscopic charcoal collected from excavations to date points to a predominance of *Picea* (Kulakovska et al., 2021).

In terms of post-depositional processes, CF1 shows clear macroscopic evidence of solifluction with stretching and overthrow of the BL, visible in Figures 12-B and 12-C. Within the micromorphological thin sections of CF1, the presence of weakly developed lenticular and granular microstructures within the red layer (SU 4-1b) gives credence to freeze-thaw related post-depositional alteration in the underlying SU 4-1b (Van Vliet-Lanoë, 1985, 2010) (Figures 14-I and 15). This includes discrete evidence of inverse grading, commonly seen in collapsed lenticular structures, and, within the upper combustion deposits, BL and MB, some of the charcoal fragment appear cracked by frost

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action (Matthiesen et al., 2013). Cappings are also visible on some aggregates within the MB deposit (Figure 13-E) (Van Vliet-Lanoë, 1985, 2010). However, due to the extensive bioturbation within the sampled sections, it is difficult to ascertain the extent of cryoturbation within the CF1 deposits at a microscopic scale.

The results of the colorimetric analysis of CF1 appear consistent to temperatures for wood fuelled combustion features. Wood fire features can potentially achieve maximum temperatures above 950°C depending on several different factors, (e.g., fuel type, amount of fuel, moisture content, conditions of the underlying substrate) (Aldeias et al., 2016; Bentsen, 2013; Hoare, 2020). High surface temperature then transfers heat down into the underlying substrate and our results of temperatures reaching 600°C in the subsurface, reddened RL layer, of CF1 are relatively consistent with those from experiments by Aldeias et al. (2016, p. 73). The diffused character of the BL and RL of CF2 made temperature estimation using the method above non-viable.

CF2 – CF2 is also an open flat hearth structure with no evidence of a stone lining or secondary features around it. Based on the sampled area of CF2, there were no preserved ash domains or lenses. The BL in CF2 is only partially preserved within the sampled section (Figure 21) with a diffused boundary between the BL and RL deposits. In stark contrast to the BL of CF1, CF2 is nearly devoid of identifiable burned plant remains, with much of the very few organic materials appearing as amorphous black nodules under the microscope. Based on our micro-observations, the BL of CF2 is considerably less dense in organic materials than the BL of CF1. Additionally, SM-09 has no burned bone fragments within either the MB or BL deposits. The microstructure of underlying SU 4-1b, the combustion deposits, and overlying SU 3-4b within SM-09 have weakly developed pedality and separation between the sedimentary materials (Stoops, 2003) meaning the microstructure

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is generally massive. The only evidence of cryoturbation is isolated lens of preserved capping, vesicles, domains of weakly developed lenticular microstructure within the RL (4-1b) and BL shown in Figure 21.

Overall, the general lack of well-preserved ash layers, combined with the fragmented nature of the bone and charcoal, suggest that both CF1 and CF2 were exposed on the surface for a prolonged period. Conditions with high wind or run off would favour the erosion of the ashes, whereas we do not see signs of dissolution and reprecipitation of the remaining ash domains. This conclusion of a stasis from deposition and exposure of the occupation surfaces is supported by extensive aerial weathering and *in situ* fragmentation of faunal remains from Korman' 9 as described by Kulakovska et al. (2021) and Bosch et al. (2024).

4.5.3 Anthropogenic Soils and Bioturbation:

The influx of organic waste and materials by humans can have a knock-on effect in terms of promoting soil fauna activity and biodiversity in the subsequent deposits (Schilt et al., 2017). At Korman' 9, the BL and MB of both features have extensive post-depositional bioturbation and pedogenesis as shown in figures 13, 16, and 17, similar to those reported by Schilt et al. (2017) at the Late Gravettian site of Grub-Kranawetberg I (Austria). The MB deposit of CF1 and CF2 developed after the use of the combustion feature and is likely the result of localized gradual mixing of loessic materials (potentially SU 3-4b) with the organic rich materials left from anthropogenic occupations, including fire use. In the MB deposit from CF1, there is clear evidence of carbonate enrichment with the formation cm-sized carbonate nodules as well as micritic hypocoating and root casts, whereas the MB deposits associated with CF2 are less developed in comparison. Similarly,

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the BL of CF2 is less rich in organic matter and charred materials than the BL associated with CF1. This could suggest that either the topsoil below CF2 was less carbonized due to burning for a shorter period than CF1 or contained less organic material syn-combustion. The latter possibility is further discussed in the section below. In contrast to the micromorphological samples from the combustion features, SM-03, taken approximately 30 cm laterally from CF1 during the initial stages (Phase 0) of excavation (Figure 12), shows only limited lenses and domains of organic rich silts which appear to be the remnants of SU 4-1a (Figure 22).

4.5.4 Fire use at Korman' 9:

Based on the morphological and compositional variation between CF1 and CF2 (including the dimensions, thickness and nature of the combustion deposits, presence and nature of post-depositional alternations), we can suggest two different explanations. The differences between CF1 and CF2 could (1) represent two distinct occupations, or (2) a single occupation with variations due to patterns in site organization and/or reflect differences in use or function.

If we consider the first hypothesis, then CF1 and CF2 would represent two distinct occupations within the same stratigraphic SU 4-1a. We currently lack the resolution to temporally confine CF1 and CF2 to create a clear time frame between the occupations and accumulations or to attest to their contemporality. The usage of CF1 and CF2 could be separated by a matter of weeks to centuries. However, we can suggest contrasts between the BL deposits of CF1 and CF2, and the distinct development of the degree of cryoturbation sedimentary signatures could indicate different depositional times between the two features. Firstly, the distinction between the presence of organics within the BL of

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CF1 and CF2 could potentially be product of several factors. One of which could be related to seasonality with the firing of CF1 corresponding to season (fall) where more organic litter maybe present on the surface and topsoil, while CF2 could have been fired during late spring or summer where organic litter is not as present in the topsoil. Conversely the occupations could be separated by some time, resulting in different conditions for the presence of organics in the topsoil. Secondly, based on our observations we can identify a distinct difference between the nature of cryoturbation related to CF1 and CF2. CF1 appears to have more clear evidence of post-depositional alteration with development of lenticular and granular structures (albeit weakly developed) within thermally altered deposits as well as surrounding substrate. While we are limited to only a single sample for CF2 (SM-09), the effects of cryoturbation are less clearly visible or well preserved on a microscopic scale. Moreover, as discussed in the section above, CF2 has weakly developed pedality and nearly no separations between peds in the sedimentary matrix. This suggests the deposition of CF2 could have taken place in slightly different environmental conditions.

Conversely, taken the second hypothesis mentioned above, CF1 and CF2 could represent the same occupation but vary morphologically based on site organization. Based on the dimensions and morphology of the CF1 structure, including the much thicker RL and BL layers (Figure 12), we can assume CF1 was used more intensely than CF2. Using morphology (namely the thickness) of the RL, it can be argued CF1 was either fired during a longer period and/or the fire was maintained at a higher temperature than CF2. As shown in experimental studies, the most significant thermal alteration of the underlying sediment takes place over the first 2 to 3 hours of burning (Aldeias et al., 2016). Moreover, the depth of rubification varies depending on the substate, presence of thermal

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insulators on the burning surface, as well as the duration and intensity of the fire use (Aldeias et al., 2016). This evidence suggests that CF1 could have been used for a prolonged period and/or fired at a higher temperature. Therefore, the variations between the two structures could be associated with site organization and settlement strategies (Binford, 1978; Binford, 1980; Clark et al., 2022; Rolland, 2018; Stapert, 1989). In a similar vein, the differences between CF1 and CF2 could be due to function. While the function of combustion features is often unclear (Aldeias, 2017; Aldeias et al., 2016), the variations of organic input could be the result of repeated refuelling of CF1 compared to CF2. The differences between the effects of cryoturbation could be localized due to several factors, such as localized drainage conditions, presence of surface matter, snow cover, etc. It is possible that the post-depositional effects of cryoturbation could represent a mosaic of different localized conditions rather than multiple events converging over time. Again, due to the extensive bioturbation in both CF1 and CF2 our conclusions should be treated with a grain of salt and future analysis and more sampling across SUs 3-4b, 4-1b and 4-1a can provide more insights into the topography of these palaeosurfaces, as well as the nature of post-depositional processes at the site.

Regardless of timing of the occupations, however, after the combustion features were used, the site was likely abandoned. The lack of ash and the fragmentary nature of the charcoal remains within CF1 and CF2 implies that the occupational debris of AL I were exposed to the elements over some time. Both combustion features were also intensively bioturbated by soil microfauna and localized plant growth. Overall, the absence of evidence for stacking or superimposed combustion features at the site, combined with the evidence of long-term exposure of the combustion residues, suggest that these features were not reutilized after their initial abandonment. Several ethnographic studies have

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shown human hunter-gatherer groups tend to reuse the same location for lighting combustion features (Mallol & Henry, 2017; Mallol et al., 2007; McCauley et al., 2020). This suggest that, if CF1 and CF2 were separate occupations, then it is likely that the timing for each of occupations was separated for a long enough period time that the initial occupation area was already buried from view. Vice versa, if they are from the same occupation then, the site was not reoccupied within the excavated portions of AL I. After the abandonment, the evidence for solifluction processes, as described by Kulakovska et al. (2021) and Bosch et al. (2024), suggests gradual movements of parts of the combustion features and other materials (shown in Figure 6) downslope.

4.5.5 Korman' 9 in context:

Similar combustion structures to CF1 and CF2 have been found in nearby sites in the Middle Dniester region. Several of which have occupations occurring during a similar period of the LGM as Korman' 9. These include the nearby sites of Korman' IV, Molodova V, and Doroshivtsi III (Haesaerts et al., 2007; Haesaerts et al., 2003; Kulakovska et al., 2015; Noiret, 2009; Noiret et al., 2021). While the combustion features at these sites are not described in detail, their presence is usually associated with potential hut-like structures or concentrations of lithic artifacts and faunal remains (sometimes interpreted as activity areas) (Chernysh, 1977, 1987; Klein, 1973; Kulakovska et al., 2015; Murphree & Aldeias, 2022; Noiret, 2009). The sites of Korman' IV (Layer 5a) and Molodova V (Layer 6) feature dozens of combustion features directly associated with activity areas (Chernysh, 1977, 1987; Noiret, 2009). Some of which, such as those associated with Layer 5a at Korman' IV, are potentially lined with limestone slabs (Noiret, 2009). Other combustion features, such as those from Layer 6 of Molodova V, have nearby secondary pit features and individual charcoal lenses that could be related to combustion feature maintenance (Chernysh, 1987;

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Noiret, 2009). Two fireplaces were found in Doroshivtsi III, Level 3, and are tentatively associated with Late Gravettian materials (Kulakovska et al., 2015). However, the lack of well described reports on the nature and components of the combustion features at these sites means that implications for understanding fire use in the Middle Dniester region remains limited (Murphree & Aldeias, 2022).

When comparing the combustion features of Korman' 9 on a larger regional scale, it can be inferred that open flat combustion features generally dominate the late and post LGM landscape (Chabai et al., 2022; Murphree & Aldeias, 2022). Flat combustion structures have been recently described at the Ukrainian Epigravettian site of Barmaky (Chabai et al., 2022). The authors describe flat, unlined combustion feature, roughly 1.36 x 0.71 m dimensionally and 0.08 m thick, though it is unclear if there is a thermally altered red layer associated with the structure (Chabai et al., 2022, p. 116). Several fireplaces were also documented in layers 5 and 4 at the Moldovan site of Cosautși, located further south on the Dniester River; although it is unclear based on their description, what their morphology is (Noiret, 2004, 2009). Other types of features have been described at the sites of Mezhyrich (Ukraine) with potential evidence of pit combustion features (Marquer et al., 2015; Marquer et al., 2012). However, none of the combustion features at Mezhyrich have been described in detail, hampering regional comparisons on pyrotechnology. Overall, more detailed studies of LGM fire use are needed to better understand how modern human populations were able to employ fire use as a tool, its structural variability, and its preservation in the archaeological record, especially in the extreme cold and arid conditions common throughout the LGM.

4.6 Concluding remarks:

Here we have presented the results of our geoarchaeological study of the combustion features of the LGM site of Korman' 9. Our study represents the first detailed micromorphological descriptions of combustion features during the height of the LGM for this region. All of the combustion features identified at Korman'9 can be described as open flat hearths. Based on our results, we can infer that CF1 was a wood fuelled, open flat combustion feature. The lack of a clear ash layer and the highly fragmented nature of the charcoal and bone fragments within the combustion feature suggest that the feature was exposed on the surface for a prolonged period. However, new datasets are needed to better understand how exposure of combustion remains during glacial periods affects the preservation of ashes and other fire residues. CF2, on the other hand, is a smaller open flat hearth with limited remaining organic materials. Additionally, it is clear from our field observations, 3D models and descriptions that both combustion features were post-depositionally altered by cryoturbation and bioturbation. As a result, we can suggest several explanations for the differences between the two combustion features: 1) two separate occupations separated by an unknown period, yet within the same stratigraphic sub-unit, or 2) same occupation but differentiated by site organization and/or function. In comparison with the limited evidence from the Middle Dniester region, open flat hearths appear to have been the primary form of pyrotechnology created by humans during the LGM. The presence of structurally more complex features (with pit and stone lined hearths) is alluded for some sites (Mezhyrich and Korman' IV) and further research into the nature and composition of these features is needed to provide a more holistic view on the use of fire during extreme cold periods (Chernysh, 1977; Marquer et al., 2012; Noiret, 2004,

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2009). Overall, more research and detailed macro- and micromorphological studies are needed to better understand the relationship between combustion features and the spatial organization of human occupations in the region. Future experimental studies should also focus on better constraining the effects of cryo-related processes on the preservation of combustion residues. In conclusion, our results provide new insights into human fire use behaviour at the height of the LGM and highlight new avenue of research for future studies in the region and beyond.

Chapter 5

Title: Simulating the effects of repetitive freeze-thaw on combustion materials.

Authors: William Chase Murphree^{1*}, Godefroy Devevey¹, Vera Aldeias¹

Affiliations: ¹ Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), University of Algarve (Portugal)

* Communicating Author

5.1 Introduction:

In recent years, there has been intense debate concerning the prevalence of Palaeolithic pyrotechnology during glacial periods in northern latitudes. A pattern was seen in Neanderthal related archaeological assemblages in southwest France, where there is a marked decrease in the evidence of fire use during glacial conditions, despite evidence for occupations of the various sites (Aldeias et al., 2012; Dibble et al., 2017; Dibble et al., 2018b; Sandgathe et al., 2011). Additionally, in chapter 3, the review of the structural evolution of pyrotechnology in the Upper Palaeolithic showed a clear gap in published descriptions of combustion features between 28,000 and 16,000 calibrated years before present (BP) (Murphree & Aldeias, 2022). This period corresponds to the maximum extension of glacial ice and extreme cold and rapidly deterioration of climate condition during the late Pleistocene. In Murphree & Aldeias (2022 - see chapter 3), we suggested three potential explanations for the lack of well described combustion features during the

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Last Glacial Maximum, specifically: lack of accessible/published datasets, absence or limited fire use by humans, or poor preservation of combustion remains due to freeze-thaw related processes. While the first two explanations are plausible, they are difficult to test experimentally. However, the degree into which freeze-thaw impacts on combusted remains can be tested experimentally (Masson, 2010).

Cryoturbation, or the mixing of materials by freezing and thawing of water within soils and sediments, is one of the widely occurring and recognizable syn- and post depositional processes affecting Eurasian Pleistocene archaeological assemblages. The central process for cryoturbation is the formation of ice lenses or ice nucleation within sediments, which can modify, redistribute, and/or contribute to the dissolution and destruction of sedimentary components (Henry, 2007; Texier et al., 1998; Van Vliet-Lanoë, 1985, 2010). The extent of frost effects is, in turn, controlled by grain-size and drainage conditions within a sedimentary matrix (Van Vliet-Lanoë, 1985, 2010). In archaeological assemblages, cultural materials such as combustion structures and features, are extremely susceptible to these freeze-thaw related processes since these are, in essence, sedimentary artifacts (Miller, 2011).

Combustion features are defined here as material and sedimentary remains of anthropogenic fire use and can broadly encompass both well-preserved hearth features to fire residues in secondary context (Mentzer, 2014). Most common type of combustion features in palaeolithic archaeology are simple flat unlined structures (Mentzer, 2014; Murphree & Aldeias, 2022). These structures generally consist of three distinct sections: an ash (white) layer where the combustion reaction and burning of fuels takes place, a black layer (burned organic topsoil or charcoal-rich deposits from incomplete burning of fuels), and a red layer (thermally altered substrate) (Aldeias, 2017; Aldeias et al., 2016; Mallol et al.,

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2013b; Mallol et al., 2017; Mentzer, 2014; Stahlschmidt et al., 2020). The upper two layers, the white and black layers, are highly susceptible to modification by wind, rain, and other natural and anthropogenic processes (Aldeias et al., 2016; Goldberg et al., 2017; Karkanas, 2021; Mentzer, 2014).

From an archaeological perspective, Pleistocene archaeological sites in northern latitudes commonly have, to varying degrees, the sedimentary signature of frost effects. Several experimental projects have focused on identifying the alteration of experimental archaeological assemblages in periglacial conditions, namely the effects of freeze-thaw on material culture such as lithic and faunal materials (Bertran et al., 2015; Bertran et al., 2010; Bertran et al., 2019; Lenoble & Bertran, 2004; Lenoble et al., 2008; Texier et al., 1998). These studies have primarily focused on macro-observations related to the redistribution, modification, and surface scattering of material culture (Texier et al., 1998). Additional studies have been done to simulate the effects of freeze thaw on different types of sediments in engineering, agricultural, and environmental studies contexts (Henry, 2007; Liu et al., 2016; Rooney et al., 2022; Starkloff et al., 2017).

Many of these experiments are designed to mimic archaeological assemblages or specific conditions which limits their applicability to a wider range of sites or conditions. While the post depositional effects of cryoturbation on sedimentary artifacts have been described by various authors in detail, experimental work looking at how these processes develop and contribute to the deformation, redistribution, or destruction of fire-related structures and residues have not been investigated (Masson, 2010). This is relevant, since the degree to which cryoturbation can displace, fragment and dissolve combustion remains can have far reaching implications in Palaeolithic archaeology. "*In-situ*" combustion features are commonly used as a marker of human occupation in an

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archaeological site as well as a central hub for activities around it, such as knapping of stone tools or the butchering of animals. Additionally, ethnographic as well as archaeological data suggest that combustion features are commonly reused (Fullola et al., 2012; Karkanas et al., 2004; Mallol & Henry, 2017; McCauley et al., 2020). The disruption or loss of these features limits the interpretations we can make about activities at the site as well as mask different occupations within a single assemblage. Additionally, the displacement, modification, and fragmentation of combustion remains like charcoal, which is commonly used for C14 dating, or biomarkers related to burned materials can potentially bias chronostratigraphic, behavioural, or paleoenvironmental interpretations.

In this chapter, we present laboratory experimental work dealing with the effects of freeze/thaw on combusted material, namely layers of ash and charcoal. The goal for this experimental project is to simulate and observe the effects of cryoturbation on a) the degree of preservation of combustion residues, and b) the visibility of combustion features in the archaeological record.

5.2 Background on freeze-thaw processes:

The way ice lenses form within a sedimentary matrix is based on the balance of temperature and availability of water within a substrate (Van Vliet-Lanoë, 1985, 2010). As the temperature decreases within a sediment, water held within the substrate crystallizes creating an ice lens (Figure 23). The formation of these ice lenses at the thermal gradient stems from suction of water from the underlying substrate to the frost front (Figure 23)(Van Vliet-Lanoë, 1985, 2010). The growth of the ice crystals is then limited by the availability of water within the substrate. As the underlying sediment below the ice lens

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becomes desiccated, new lenses will then form further downwards as the freezing line and capillary fringe moves lower in the substrate (Figure 23).

Frost susceptibility in sediment or soils is also influenced by both the texture and grain size distribution (Van Vliet-Lanoë, 1985). Ice lenses form more rapidly in silty, loamy to sandy loam sediments (Bertran et al., 2015; Van Vliet-Lanoë, 2010). This is due to the greater ability for capillary water to move between the grains (Bertran et al., 2015; Van Vliet-Lanoë, 2010). Ice lensing can also develop rapidly in more heterogenous, poorly graded sediments where water drainage is imperfect.

A common feature within sediments that have undergone freezing and thawing is the formation of lenticular and platy microstructures within the sedimentary matrix (Van Vliet-Lanoë, 2010). These freeze-thaw fabrics form small angular or blocky peds via ice lensing and the cryodesiccation of the underlying substrate (Van Vliet-Lanoë, 2010). In repetitive freeze/thawing cycles a banded fabric can be produced, where fine particles such as clays or silts form layers capping the upper face of the platy or lenticular aggregates during each freeze-thaw cycle (Van Vliet-Lanoë, 1985). Also common in near surface layers of sediments are granular microstructures where aggregates become more rounded due to repetitive cycles, continual plastic deformations and micro erosion (Van Vliet-Lanoë, 2010).

As a result of the interplay between these influencing factors, the ideal conditions for the formation of ice lensing are within moist loamy or sandy loam sediments in which ice lensing is progressive (Van Vliet-Lanoë, 2010). Waterlogged sediments create large ice bodies at the surface due to the continual growth of ice crystals during freezing, preventing the formation of subsequent ice lenses in the subsurface; while, on the other

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hand, the lack of water in dry sediments means no ice nucleation and, therefore, no sedimentary cryogenic fabrics are formed (Van Vliet-Lanoë, 1985, 2010).

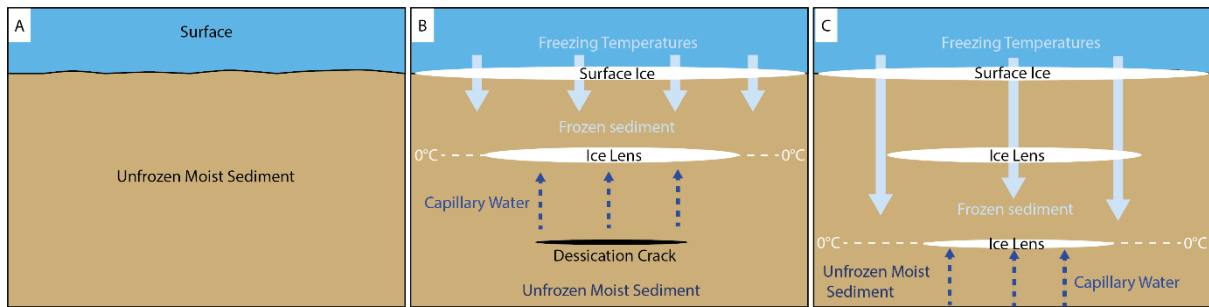


Figure 23: Formation of ice lenses within a sedimentary matrix. A) unfrozen moist matrix B) as the surface temperature drops, the ground below begins to freeze. Ice lenses then form at the interface of frozen and unfrozen moist sediment starting at the surface and migrating downwards as the ground below freezes. The newly forming Ice lens sucks water upwards from the unfrozen sediments below. As the capillary water in the unfrozen moist sediment becomes depleted, desiccation cracks form (cryodesiccation). C) New ice lenses form or nucleate within the former desiccation cracks as the thermal gradient migrates downward. Image is based on Van Vliet-Lanoë (1985).

5.3. Materials and Methods

5.3.1 Experimental design

In this experiment, we tested the effect of up to 60 freeze-thaw cycles on controlled and calibrated layers of ash on top of charcoal within or on top of an experimental substrate. In addition to the number of freeze-thaw cycles (0, 1, 10, 30, 60), we varied the positions of the combustion residues (surface or buried), moisture content (0%, 50% and 100%), and the duration of freezing, with control samples for each treatment. The experimental design was selectively cross-factorial (Figure 24), and each

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treatment had three replicates. The materials were contained within a PVC (Polyvinyl chloride) cylinder with a cap at the base (Figure 25). These cylinders were frozen and thawed repeatedly over the course of the experiment. All experimental work and analysis were conducted in the Laboratories at the Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), University of Algarve, Portugal

Number of cycles	0	1	10	30	60	1
Position of the ash (grey) and charcoal (black) layers						
Moisture content						
Time frozen (Hours)	0	16	158	423	1290	1290

Figure 24: Outline of experimental variables, where we varied the number of freeze/thaw cycles: 0 (unfrozen), 1 (single cycle and continuously frozen for 1290 h), 10, 30, and 60 cycles; the position of the combustion residues (buried or surface); the moisture content (0%, 50%, and 100% or full capacity without excess of water); and the time frozen.

5.3.2 Experimental Variables

Combustion residues

The ash layer was made of 20 grams (g) of a mix of burnt wood screened to <500 µm. The average thickness of the ash layer is roughly 7mm in thickness (Figure 25). These deposits were placed on top of a charcoal layer of 20 g of commercially available charcoal (*Acacia sp.*) ground down and screened to <2 mm, resulting in a layer of approximately 7 mm in thickness (Figure 25).

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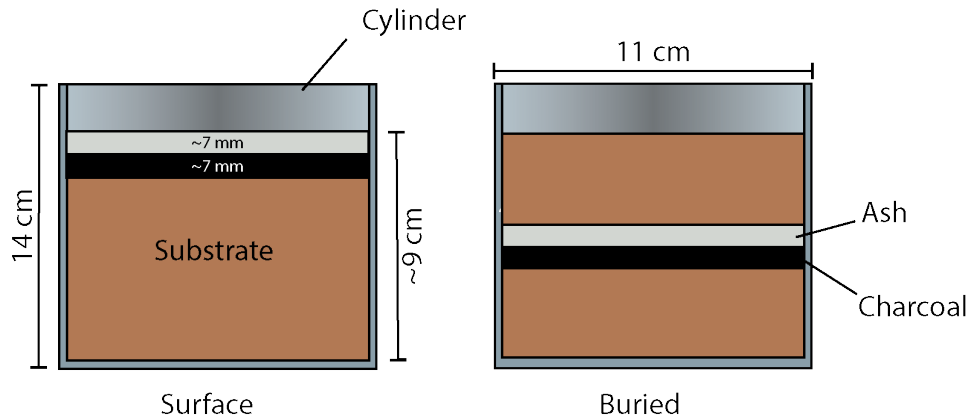


Figure 25: Diagram showing the experimental model design. The right shows the surface samples with the placement of the ash and charcoal on the surface of the substrate. The left shows the buried samples with the buried ash and charcoal layers placed between two substrate layers.

Experimental substrate

These components were then either positioned on top or buried in siliciclastic sediments made of a mixture of 90% sand and 10% clay, which is classified as a loamy sand. These non-combusted experimental sediments were analysed by Fourier Transform Infrared Spectroscopy (FTIR) using a Thermofisher Nicolet iS5 FTIR spectrometer for mineralogical characterization. Infrared measurements were collected in KBr pellets with approximately 5 mg of finely ground powder of the combined substrate as well as the individual sand and clay components with ratio of 1:99 KBr. All sediments were dried prior to the experiment. The spectra were recorded in transmission mode with 16 scans at 4 cm^{-1} resolution between $4000\text{-}400\text{ cm}^{-1}$ wavelengths. The obtained spectra were compared with reference U.S. Geological survey libraries to aid identification (S.I.- Chapter 5). Our infrared spectra results suggest a 95% match of the clay with illite, which is a non-swelling clay mineral. The sand spectrum suggests an 85.5% match with quartz. Clay naturally

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aggregates and some aggregates are homogeneously present throughout the sedimentary matrix. Each cylinder contained 1000 g of experimental sediment.

Moisture content

The maximal water capacity (100% or full saturation without excess water) of the experimental sediment was determined to be on average 234.8 ± 7.9 ml/kg (average and standard error calculated over 5 repetitions). The detailed protocol for calculating moisture capacity can be found in the S.I. – Chapter 5. In brief, we placed 500g of sediment bottomless cylinder with a filter at the base. We then added a 150 ml of water to the sediment and allowed the excess water to be filtered out through the base of the tube. The results were calculated using mass (dry -wet weight) and subtraction (total water added- excess water). This protocol was repeated 5 times with the average between the two methods equalling approx. 118 ml per 500 g of sediment. We experimented with three levels of moisture in sediment: 100% of maximal water capacity, 50% and dry sediment.

Experimental Method

The treatments for zero cycles (Figure 24) were stored in a climate-controlled room for the duration of the freezing and thawing cycles. For the cylinders undergoing freeze/thaw, these were placed on top of a layer of experimental sediment within a plastic container and then, once in place, the space between each experimental cylinders were filled with the experimental sediment. The surrounding sediment acts as an insulator limiting the heat exchange from the base and the sides of the cylinders to the top of the cylinder only. Once the sediment and combustion materials were added, the prepared

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cylinders were covered in plastic wrap to mitigate changes in the moisture content inside the experimental cylinders due to evaporation

The cylinders were placed inside a Becker BCF3900N freezer (Figure 36). The timing of each cycle was based on two extra control cylinders filled with the same experimental substrate in which thermal probes were placed on the surface and at the middle of the cylinder. Temperature data was collected using 10-min intervals and stored on 4channel PCE-T390 contact thermometer device. The freezer was turned on and closed until the probe for the internal temperature of the control cylinder reached at least -2°C , at which point the freezing was stopped and the door was opened to begin thawing to $\geq +2^{\circ}\text{C}$.

Post-experimental treatment

When the treatment of the cylinders was terminated, they were placed in an incubator (INCU-line 750 CR Premium) to dry for a period of approximately 2 weeks at 60°C to remove all water from the samples. To produce micromorphological thin sections and visualization of the experimental sediments in profiles, a series of holes were drilled on the outer surface of each cylinder for the resin impregnation process to be evenly distributing throughout the entire sample. Every sample was impregnated using a polystyrene mixture of 700 ml of polyester resin, 300 ml of styrene, and 7 ml of Methyl Ethyl Ketone catalyst (MEKP). Once partially hardened, the resin impregnated samples were placed back into the incubator to dry. The fully harden samples were then bisected through a random diameter with a diamond bladed table saw and photographed (Figure 26).

5.3.3 Analytical methodology

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The analysis focused on three main aspects and scales, specifically macroscopic analysis, micromorphological analysis and micro X-Ray Fluorescence (μ XRF) elemental mapping.

Macroscopic observations

We used two metrics that were indicative of the quality and integrity of the layers: 1) the average thickness of the layer at the centre of the cylinder (with five distinct measures taken at intervals of 1 cm), and 2) the irregularity of the layer, measured as the coefficient of variation of the average thickness. The coefficient of variation of thickness was log₁₀-transformed.

For the analytical plan, we first tested the factors of variance based on the experimental design. For this, we tested the effect of the experimental variables (residue, moisture, position of the feature) among samples that were never frozen. We then compared our results to our 60- cycles cylinders. We then tested the effects of factors based on the number of cycles and with the moisture content being constant (100%). To analyse our data, we used linear models specifically analyses of variance (ANOVA) and analyses of covariance (ANCOVA), using stepwise backward approach starting with all possible interactions. In case of a significant triple interaction between factors, we did subset the data based on position (buried or surface) and layer (ash or charcoal), to explore other factors. We then used ANOVA to further observe double interactions. In case of significant interaction between a factor and a covariable, we used a spearman rank nonparametric test dissecting the relationship between the number of cycles and average thickness, separating positions and layer. We adopted parametric statistics because, while our sample size is relatively small for each treatment ($n=3$), the design was balanced. For

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each test, we also checked the homogeneous dispersion of the residuals of the model, and that the relationship between fitted values and true values were not skewed. The statistical analysis was conducted using the stats packages within RStudio (Team, 2020). The results were rounded to three decimal places and results less than 0.001 are shown as <0.001. The code for the statistical analysis and full results can be found in S.I

Micromorphological data

For the micromorphological analysis, 20 thin sections were produced by randomly selecting a single sample representative of each treatment. The bisected sample was then trimmed to create a 7.5x5x3 cm block. The thin sections were produced by Spectrum Petrographic (Vancouver, USA), with a size of 7.5 cm x 5 cm and 30 μ m thick. The thin sections were scanned with an Epson flatbed scanner using 3200 dpi resolution and RGB photometric interpretation. The sections were analysed using a Nikon stereoscopic microscope (Eclipse SMZ25 / with camera Fi3Binocular) at magnifications ranging from 0.5x to 20x and with a Nikon petrographic microscope LV100ND with Ds/Ri2 Camera at magnifications ranging from 20 to 400x both in Plane-polarized and Cross-polarized light (PPL, XPL, respectively) at the Microscopy Laboratory "MICROLab" at ICArEHB.

Micromorphological descriptions and nomenclature was done following Stoops (2003).

μ XRF elemental data

Micro X-ray fluorescence (μ XRF) elemental mapping focused on visualizing the development of freeze-thaw related features on fully saturated thin sections produced from the micromorphological analysis. This was done to further support the findings from micromorphological analysis and give a more detailed visual aid for identifying freeze-thaw structures. We used a Bruker M4 tornado plus equipment with analysis taken under

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vacuum below ~2 mbar pressure and using a Rhodium x-ray tube. The acquisition size was 1700 pixels in width and 2200 in height. Pixel size was 20 µm with 20 ms per pixel. The elemental maps were analysed qualitatively focusing on spatial distribution and presence or absence of elements of interest, specifically: mapping common elemental components for the ash (calcium), clays (aluminium and iron), and sand (silicon).

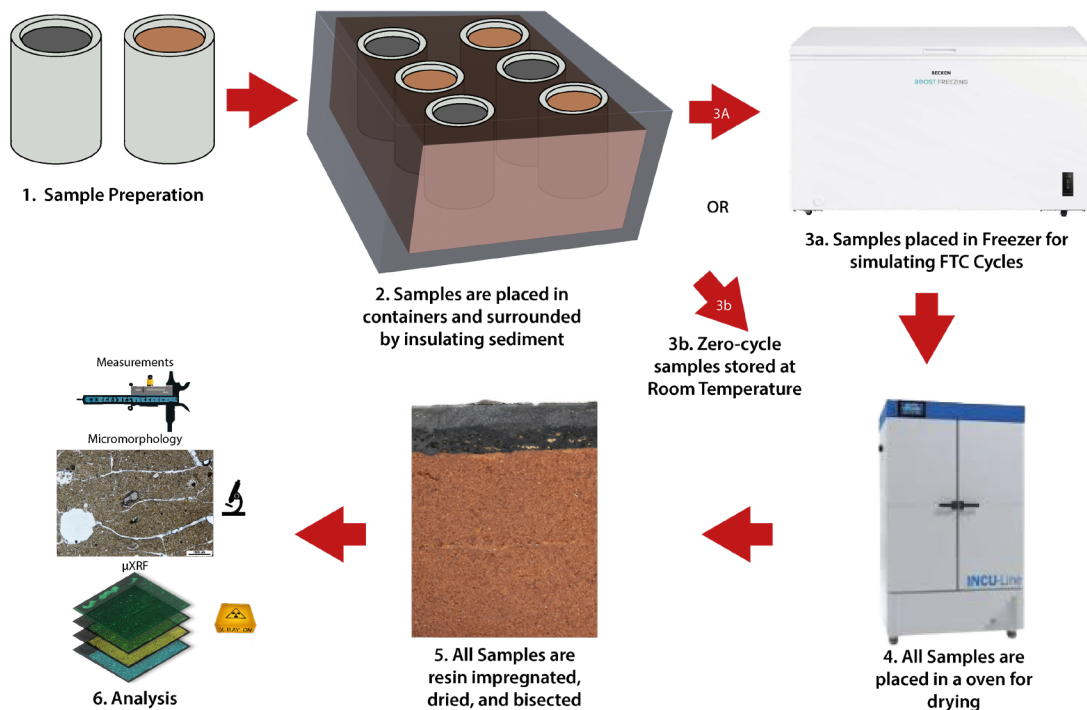


Figure 26: Outline of the experimental and analytical workflow

5.4 Results

5.4.1 Macroscopic Observations.

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Effect of number of cycles and moisture content on average thickness and regularity

Layer thickness

After using the backwards step by step procedure for the ANCOVA on average thickness, our results showed three triple interactions were significant (Table 3). We thus subsetted the data by layer and position to analyse the double interaction between moisture content and number of cycles using an ANOVA. Our results show several distinct patterns (Figure 27). Firstly, the interaction between number of cycles and moisture content was significant only in the surface ash layer ($F_{(1,14)} = 4.731, p = 0.047$). This shows that the never frozen surface ash layer did not vary in size regardless of moisture in the sample, whereas when frozen 60 times, the ash layer thinned with increased moisture. In the surface charcoal layer, moisture content was a significant factor in variability ($F_{(1,14)} = 8.281, p = 0.012$), meaning that regardless of being frozen or not, layers of charcoal with moisture were thicker than dry ones. There was no significant difference in the buried ash samples regardless of the treatment. Finally in the buried charcoal there was a significant interaction between the number of cycles and moisture content ($F_{(1,14)} = 7.711, p = 0.015$), where the 60 cycles have introduced variance in the thickness that we do not observe in samples that were never frozen.

*Table 3: Effect of freeze-thaw on the average thickness, based on moisture content (Water), number of cycles (Nb_Cy), position (buried or surface), and Layer (ash or charcoal). Significance index * for p values $P < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$. Note: results are rounded.*

Average Thickness (Nb_Cy (0,60) * Water)

	Df	Mean Sq	F value	p value	Sig
Position:Layer:Water	3	10.79	9.983	<0.001	***
Position:Layer:Nb_Cy	3	3.75	3.472	0.022	*

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Position:Water:Nb_Cy	2	5.83	5.392	0.007	**
Position	1	26.56	24.565	<0.001	***
Layer	1	121.49	112.379	<0.001	***
Water	1	0.42	0.388	0.536	
Nb_Cy	1	1.45	1.34	0.252	
Residuals	59	1.08			

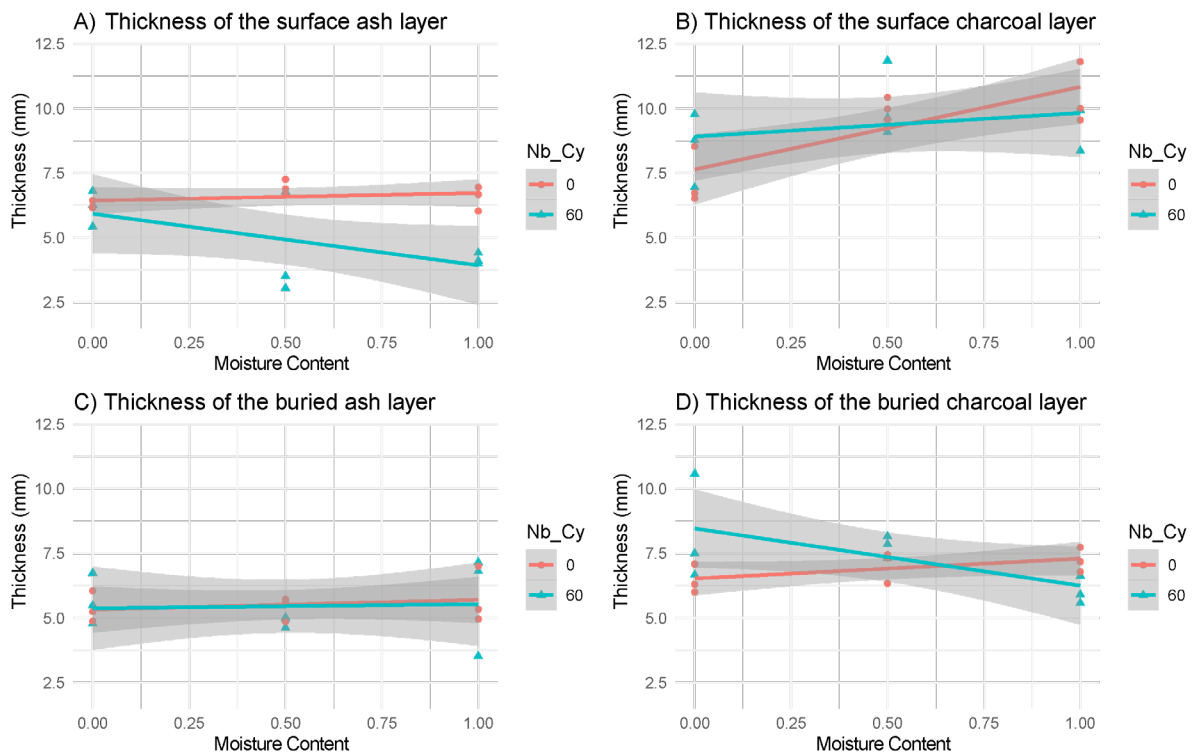


Figure 27 Scatterplot showing the variability of thickness of the layers of ash and charcoal based on position (surface/ buried) and moisture content (0.00 – dry, 0.50, or 1.00 - fully saturated). A) Thickness of surface ash remains relatively constant regardless of moisture content at 0 cycles, however after 60 cycles, the thickness of the surface ash decreases in relation to the amount of moisture. B) Surface charcoal is significantly effected by the moisture content in the sediment. C) Buried ash layer maintains the same thickness

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regardless of amount of moisture or number of cycles. D) Within the buried charcoal there is a significant interaction between the number of cycles and moisture content.

Irregularity

Table 4: Effect of freeze-thaw on irregularity, based on moisture content (Water), number of cycles (Nb_Cy), position (buried or surface), and Layer (ash or charcoal). Significance index * for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$. Note: results are rounded

Regularity

	Df	Mean Sq	F value	p value	
Position:Layer:Water	3	0.27775	6.532	0.001	***
Position:Layer:Nb_Cy	3	0.20744	4.879	0.004	**
Position:Water:Nb_Cy	2	0.14138	3.325	0.043	*
Layer:Water:Nb_Cy	1	0.09215	2.167	0.146	
Position	1	0.22604	5.316	0.025	*
Layer	1	0.3097	7.284	0.009	**
Water	1	0.12715	2.99	0.089	
Nb_Cy	1	0.27196	6.396	0.014	*
Residuals	58	0.04252			

Meanwhile the results for the ANCOVA on irregularity of layer had three significant triple interactions shown in Table 4. After subsetting the data for the ANOVA, our results showed a significant interaction between the number of cycles and moisture content only on the surface ash ($F_{(1,14)} = 7.648$, $p = 0.015$). The surface ash became more irregular after

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60 cycles (Figure 28). None of the interactions or single factors of the other layers by position analysis were significant (Figure 28). Importantly, there was no significant difference in the irregularity of the layers across samples that were never frozen, suggesting that the protocol we followed to standardize placement of combustion material (i.e., the assembly and placement of materials in our experimental cylinders) was consistent.

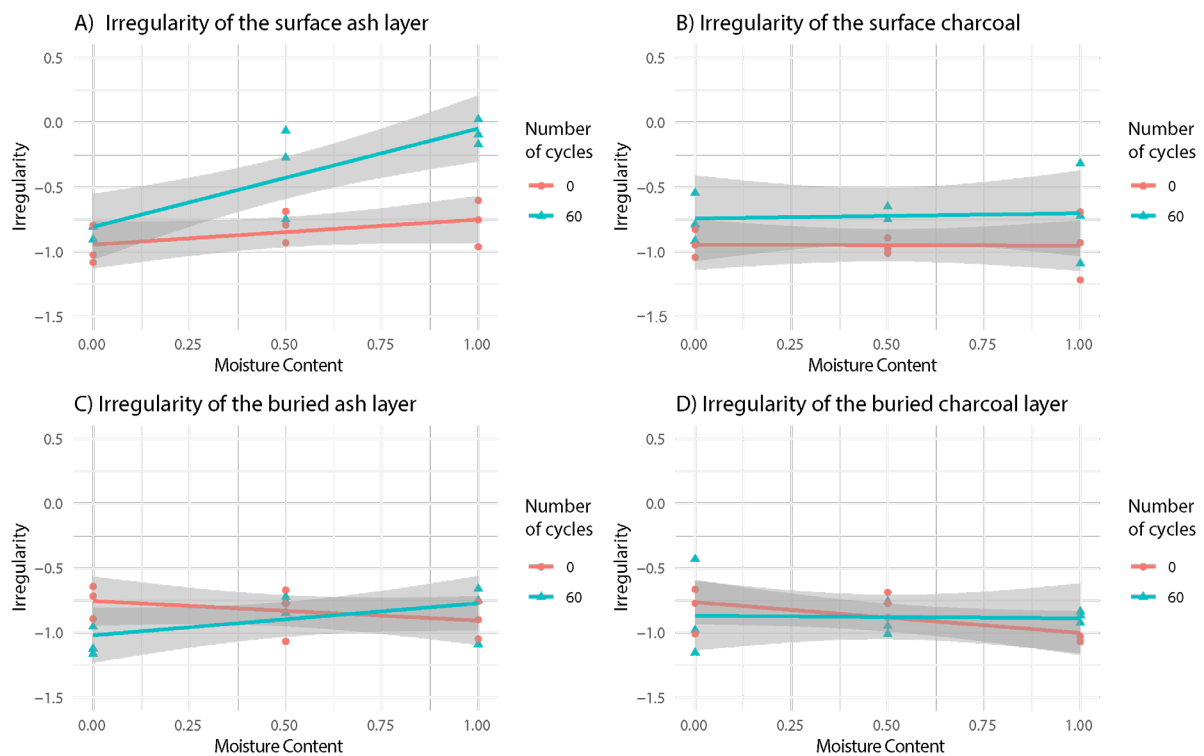


Figure 28: Scatterplot summarizing the variability of regularity of the layers of ash and charcoal based on position (surface/ buried) and moisture content (0 – dry, 50%, or 100% fully). A) Surface ash remains is significantly effected by the interaction of number of cycles and moisture content. The surface ash layer becomes more irregular after 60 cycles. B, C, D) the Irregularity of the surface charcoal as well as buried ash and charcoal were not statistically significantly altered.

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Effects on the average thickness and irregularity by number of cycles

Table 5: The interactions between number of cycles (Nb_Cy), position and layer (ash or charcoal) on the average thickness. Moisture content is 100% in all sample considered.

Note: the results are rounded

Average Thickness

	Df	Mean Sq	F value	p value	
Layer:Position: Nb_Cy	1	5.78	6.476	0.013	*
Layer:Position	1	12.9	14.449	<0.001	***
Layer:Nb_Cy	1	1.26	1.409	0.240	
Position:Nb_Cy	1	5.08	5.689	0.020	*
Layer	1	88.03	98.576	<0.001	***
Position	1	51.82	58.032	<0.001	***
Nb_Cy	1	10.43	11.68	0.001	**
Residuals	64	0.89			

The interactions between number of cycles (Nb_Cy), position, and layer type on the average thickness are summarized in Table 5. Firstly, the results, showed a single significant triple interaction between layer, position and the number of cycles ($F_{(1,64)} = 6.476$, $p = 0.013$) (Table 5). We then tested the relationships between the number of cycles and the average thickness based on position and layer using a Spearman non-parametric correlation test. Our results show that moderate (± 0.40 to ± 0.59) negative correlation between the number of cycles and the average thickness of the surface ash layer, which is

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statistically significant ($r_s = -0.5439189$, $n = 9$, $p = 0.020$) (Figure 29 A). None of the other tests showed a significant correlation.

Table 6: The interactions between position, layer, and number of cycles (Nb_Cy) on regularity. Moisture content is 100%. Results are rounded.

Regularity

	Df	Mean Sq	F value	p value	
Position:Nb_Cy	1	0.2212	4.832	0.031	*
Position	1	0.1823	3.983	0.05	
Nb_Cy	1	0.6223	13.593	0.001	***
Layer	1	0.9971	21.781	<0.001	***
Residuals	67	0.0458			

The ANCOVA on the irregularity of the layer showed in a significant interaction between position and number of cycles (Nb_Cy) ($F_{(1,67)} = 4.832$, $p = 0.031$), shown in Table 6. In this case, the surface ash layer (Figure 29 B) became more irregular as the number of cycles increased. Figure 29 shows the results of our statistical test in more detail.

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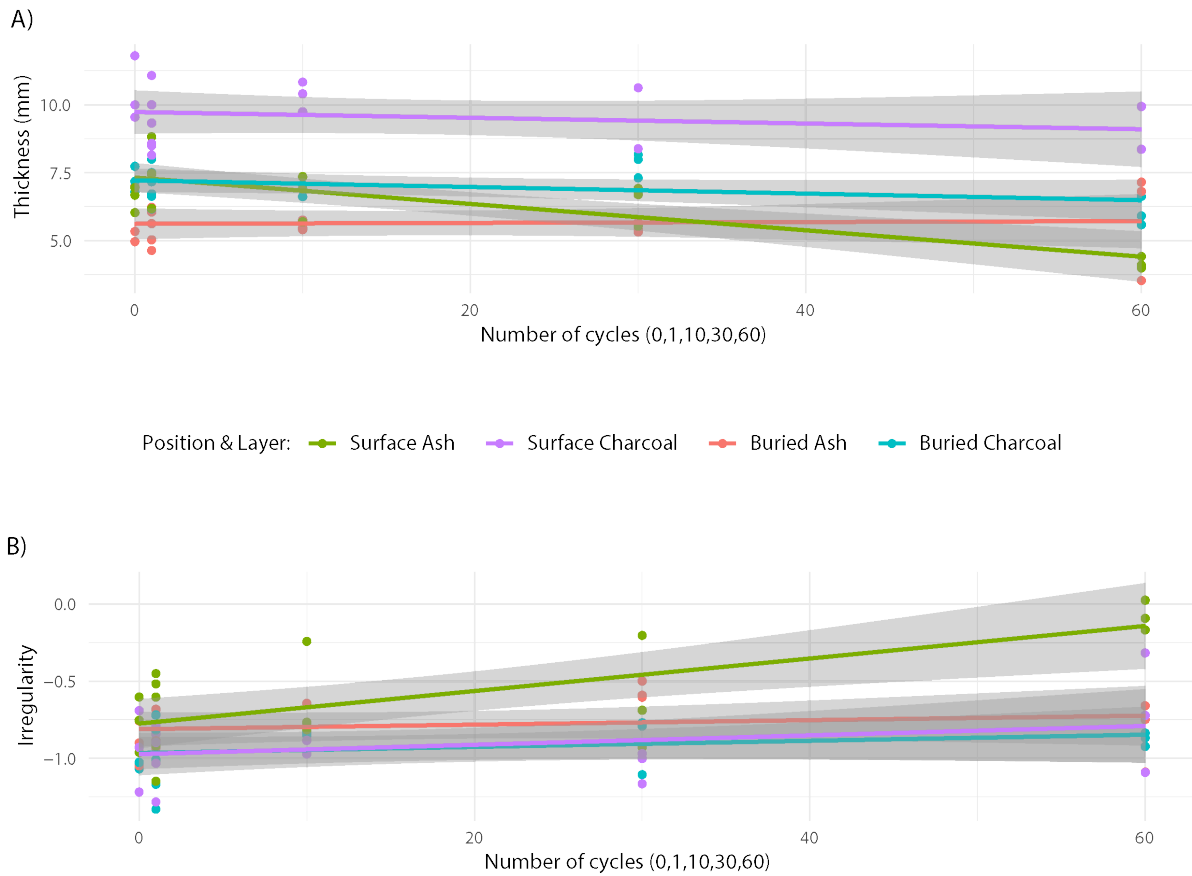


Figure 29: Scatterplot summarizing changes to the thickness (A) and irregularity (B) of the ash and charcoal layers based on position (surface or buried) and number of cycles (0,1,10,30,60). Only the surface ash shows a significant change in thickness (green line) as well as becoming more irregular (green line) as the number of cycles increases. The thickness and regularity of the surface charcoal as well as the buried ash and charcoal remain relatively constant regardless of the number of cycles.

Effect of time frozen on average thickness and irregularity

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Table 7: Effect of four-way interaction between number of cycles (Nb_Cy), time frozen, position, and layer on the average thickness and irregularity. Note: the results are rounded

Average Thickness					
	Df	Mean Sq	F value	p value	Sig
Nb_Cy:Time_frozen:Position:Layer	4	13.064	6.127	<0.001	***
Residuals	31	2.132			
Regularity					
	Df	Mean Sq	F value	p value	Sig
Nb_Cy:Time_frozen:Position:Layer	4	0.4373	8.713	<0.001	***
Residuals	31	0.0502			

Table 7 outlines the results of the ANOVA, which shows a high significant interaction between the four factors on the average thickness and regularity of layers. We again subsetted our results to explore the relationship between time frozen and the number of cycles based on position and layer. The results revealed that the number of cycles had a significant main effect on the average thickness of the surface ash layer ($F_{(1,6)} = 52.911$, $p = <0.001$). None of the other results were statistically significant. Similarly, considering the regularity by position and layer, only the regularity of the surface ash layer was statistically significantly affected by the number of cycles ($F_{(1,6)} = 11.255$, $p = 0.015$). The results are shown in Figures 30 and 31 below.

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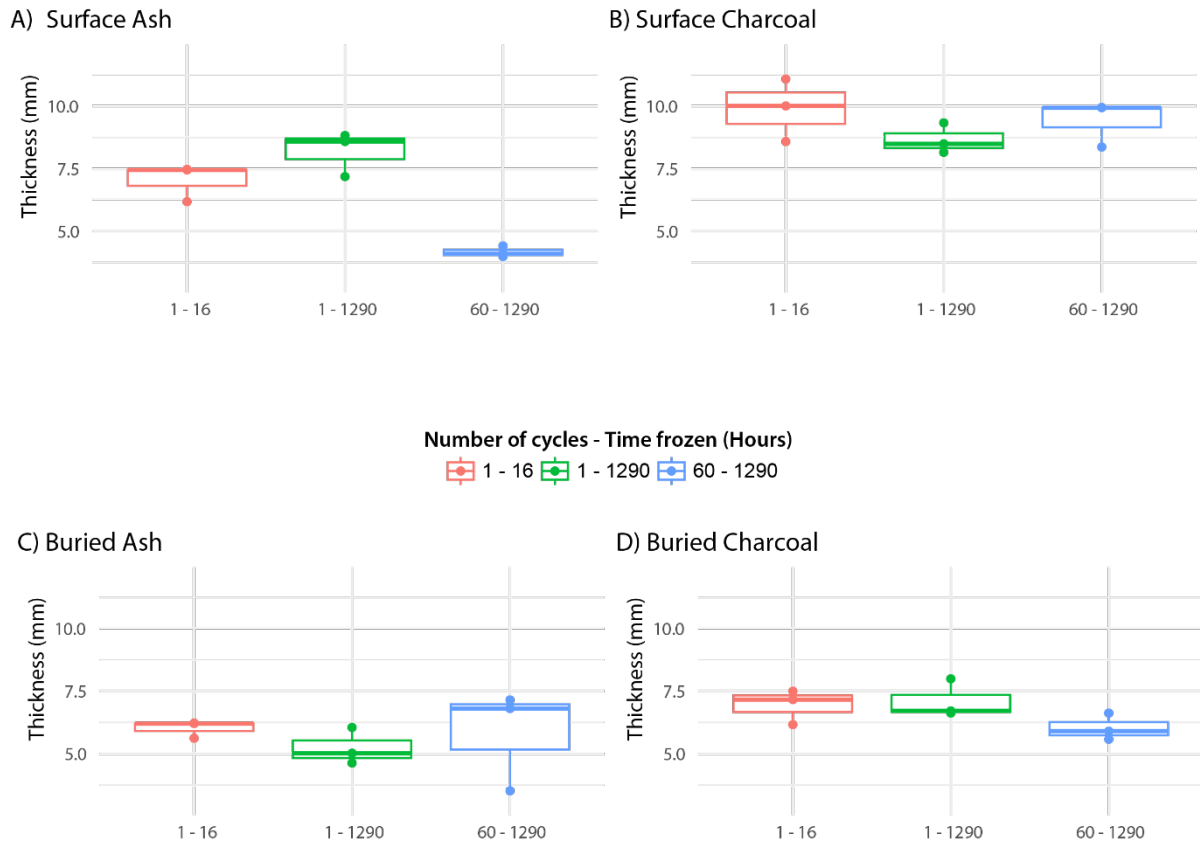


Figure 30: Box plot summarizing the effect of time frozen compared to the number of cycles on thickness based on the position (surface or buried) of the ash and charcoal layers. Number cycles and time frozen are as follows: 1 cycle for 16 hours, 1 cycle for 1290 hours, 60 cycles for 1290 hours frozen.

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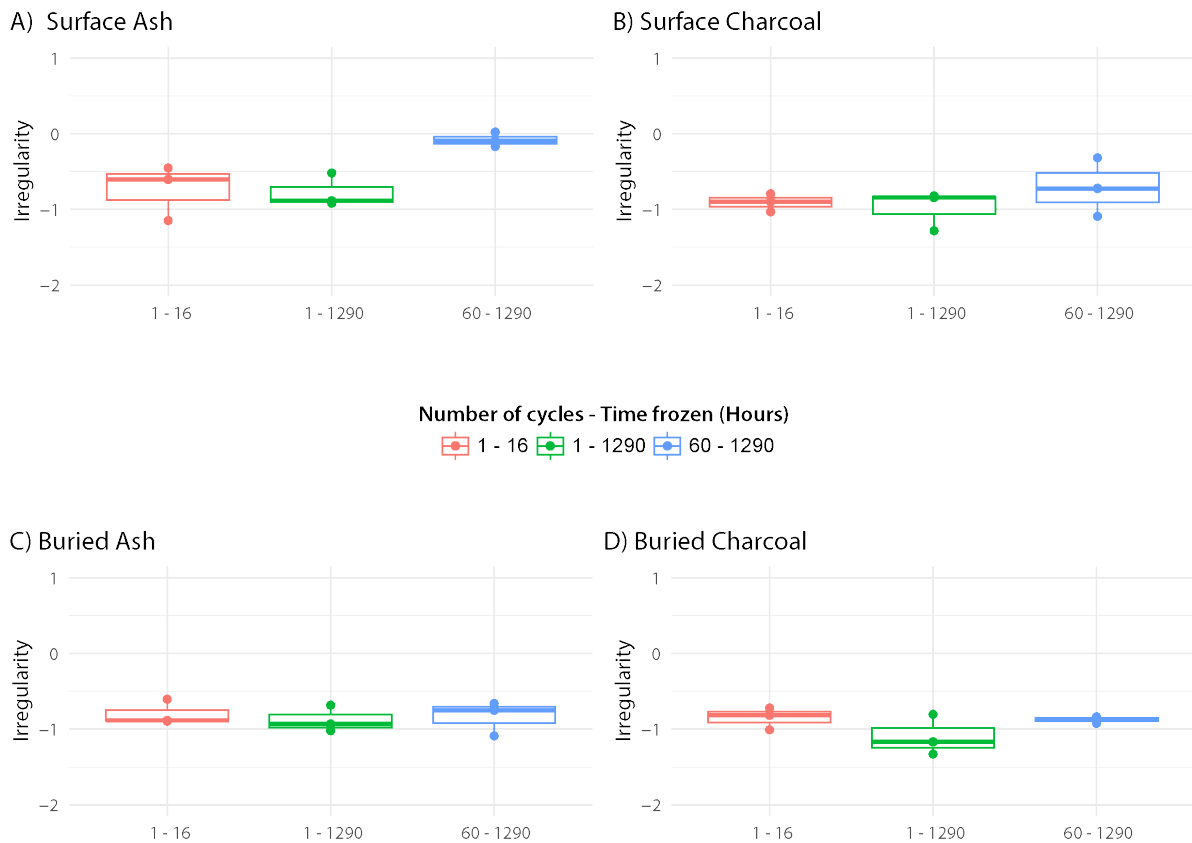


Figure 31: Box plot summarizing the effect of time frozen vs number of cycles on irregularity based on the position (surface or buried) of the ash and charcoal layers.

Number cycles and time frozen are as follows, 1 cycle. 16 hours, 1 cycle. 1290 hours, 60 cycles. 1290 hours frozen.

5.4.2. Micromorphological observations

Non frozen samples

Within all of our zero cycle samples (non-frozen, dry, 50% and 100% moisture content, both buried and surface combustion remains) the substrate used consists of a well sorted clayey sand with a single spaced fine enaulic and chitonic c/f- related (coarse to fine) distributions (Stoops, 2003). This means that the smaller fine-grained components

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(clay minerals) form aggregates within the spaces between the larger units (sand-sized quartz), as well as clays creating a coating around some of the quartz grains (Stoops, 2003). These general observations for the c/f related distributions and composition of the substrate are consistent throughout the experiment regardless of treatment type.

The charcoal layer consists of angular to semi angular fine to coarse grain charcoal fragments ranging from 2mm - <500µm in size. Across all zero-cycle samples, the charcoal layer has a porous crumb microstructure in which the aggregates are clustered together with only partial accommodation and moderate separation between peds. These void spaces between peds are generally simple packing voids and vugh like void spaces between larger charcoal fragments.

The ash remains are a mixture of pseudomorphic ash crystals, very few charcoal fragments, and few humic plants remains. The presence of the latter two is consistent with incomplete combustion (Karkanias, 2021). Some of the ash material remains are found in fibrous aggregates. Within the zero-cycle samples, the microstructure of the ash layer varies based on position and moisture content, as shown in Figure 32. In the dry sample (Figure 32 A), the microstructure is generally massive. The microstructures for the moistened surface layers appear to have a complex microstructure with the layer being relatively massive at the base while becoming more spongy or pillowy towards the top of the layer (Figures 32 B and C). In the buried samples, the 50% saturated sample and the dry sample have massive microstructures (Figures 32 D & F), while the 100% saturated sample has some planar voids as well as a semi granular microstructure near the upper interface with the overlaying substrate (Figure 32 F).

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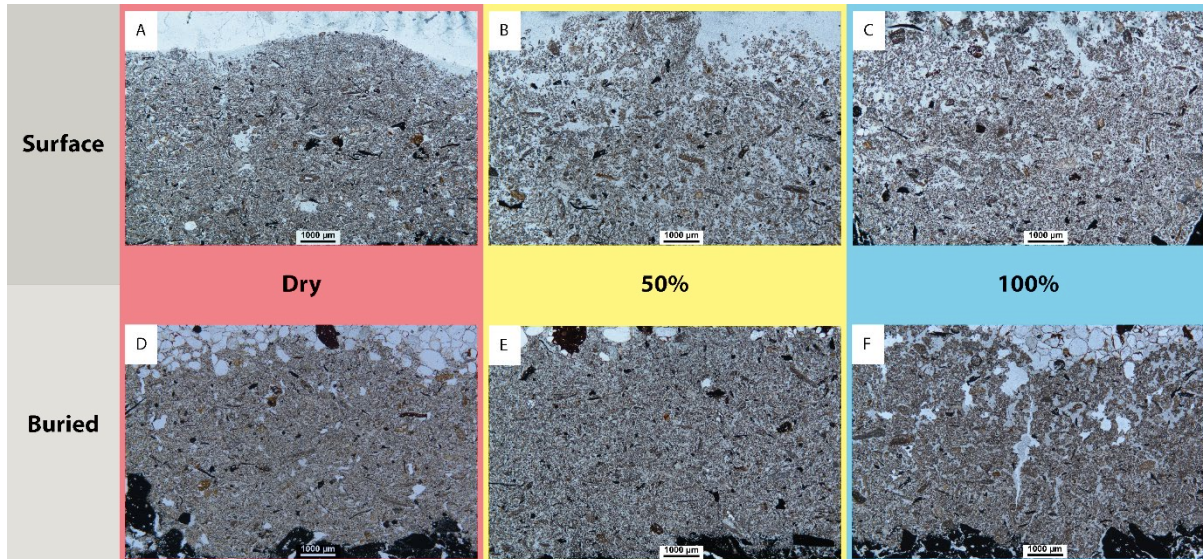


Figure 32: Photomicrographs showing the variability of the surface and buried ash layers of the zero cycle samples based on moisture content. All samples have a scale of 1000 μm and are in PPL. A) the dry surface samples have a massive microstructure. B) and C) show the 100% and 50% moisture content surface ash layers. Both samples have complex microstructures that grade from more massive at the base to more spongy or pillowy towards the top of the layer. D) and E) show the ash layers of the dry and 50% moisture content zero cycle samples, respectively. Both samples have dense massive microstructures. F) vertical cracks formed within the 100% moisture content buried ash layer.

Surface samples

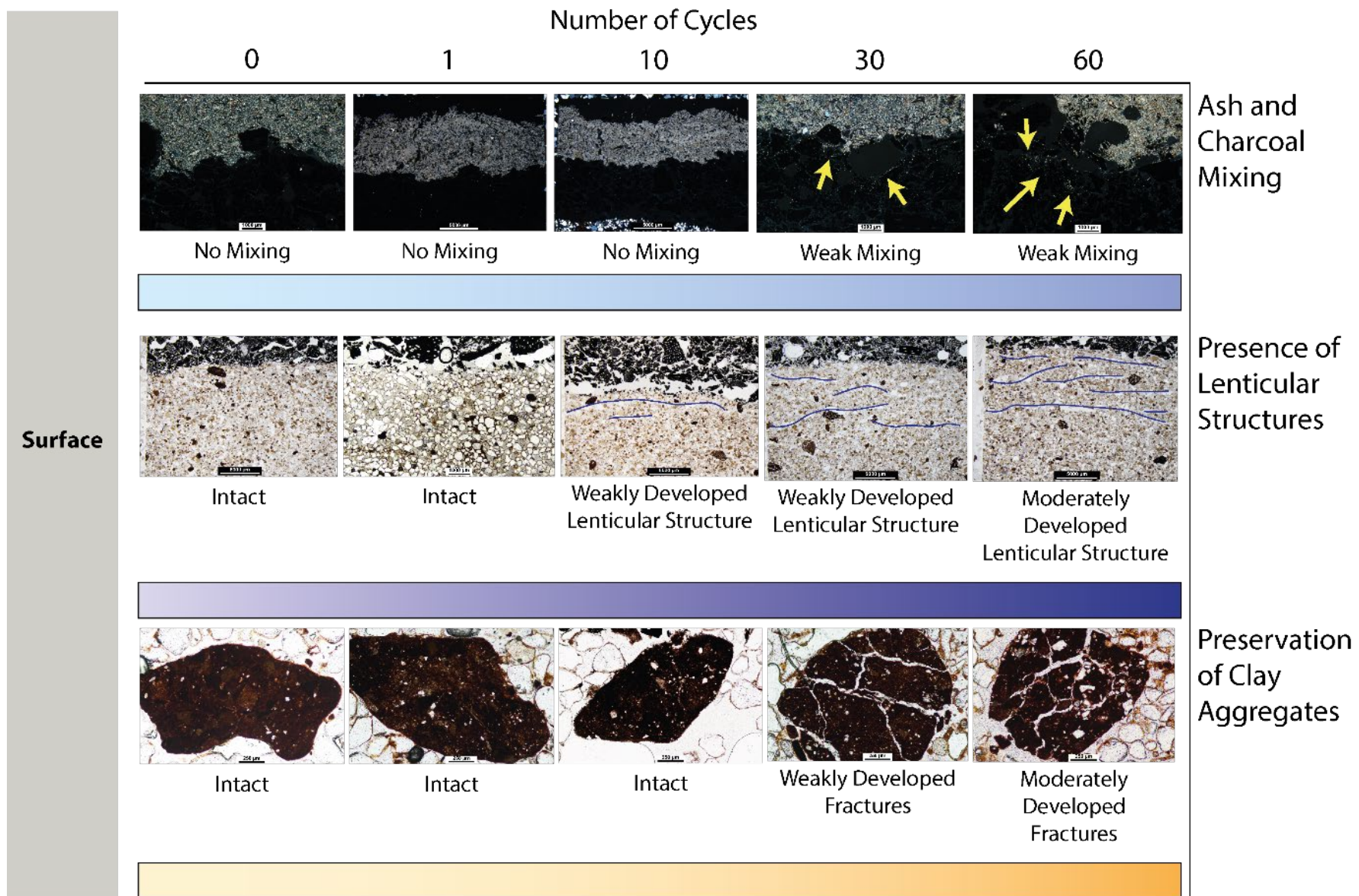
Within the substrate, there is clear evidence for the progressive development of freeze-thaw related structures in samples with 100% moisture content, shown in Figure 33. There is a clear progressive formation of lenticular structures directly below the ash and charcoal layers starting at around the 10th cycle and becoming more moderately developed by the 60th cycle. As the number of cycles increases, the amount of ice lensing

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also increases, creating greater separations between the aggregates of sediment particles (peds) (Stoops, 2003). In addition, clay aggregates found throughout the experimental substrate become more fragmented with successive freezing and thawing cycles. The degree of fragmentation of these aggregates seems to increase relative to the number of cycles (Figure 33). There is, however, not clearly mixing visible in any of the samples between the experimental substrate and overlying combustion residues, regardless of the number of cycles.

Within the charcoal layers, the effects of repeated cycles of freeze-thaw are not clear. In some samples, charcoal fragments appear to have fragmented due to freeze-thaw (Figure 34 C, green arrow). However, it is not clear how common or to what extent this has occurred. At the interface between the ash and charcoal layers, there appears to be a weak degree of mixing between the ash and charcoal layers (Figure 33). However, the ash layer remains relatively intact. The internal structure of the ash layers within the surface samples varies considerably from sample to sample depending on the treatment, time frozen, and moisture content (Figure 34). The ash layers within the dry sample (Figure 34 A), as well as the single short duration cycle (100% moisture content), mirror those dry (zero cycle samples) with a generally massive microstructure. The sample with 50% moisture content (Figure 34 B), has relatively more pillowy microstructure after 60 cycles. Surface ash layers with 100% moisture content after 60, 30, and 10 cycles have very dense massive microstructure with few vesicles. In the sample that was frozen for a single long cycle (1290 hours continuously frozen), the ash layer has several vertical and radiating cracks throughout the microstructure of the ash layer (Figure 34 D).

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Figure 33: Microscopic changes within the experimental surface samples based on the increasing number of cycles. The photomicrographs shown above were shot in XPL (ash and charcoal mixing photomicrographs) and PPL (remaining photomicrographs) and at various scales shown in the pictures above.

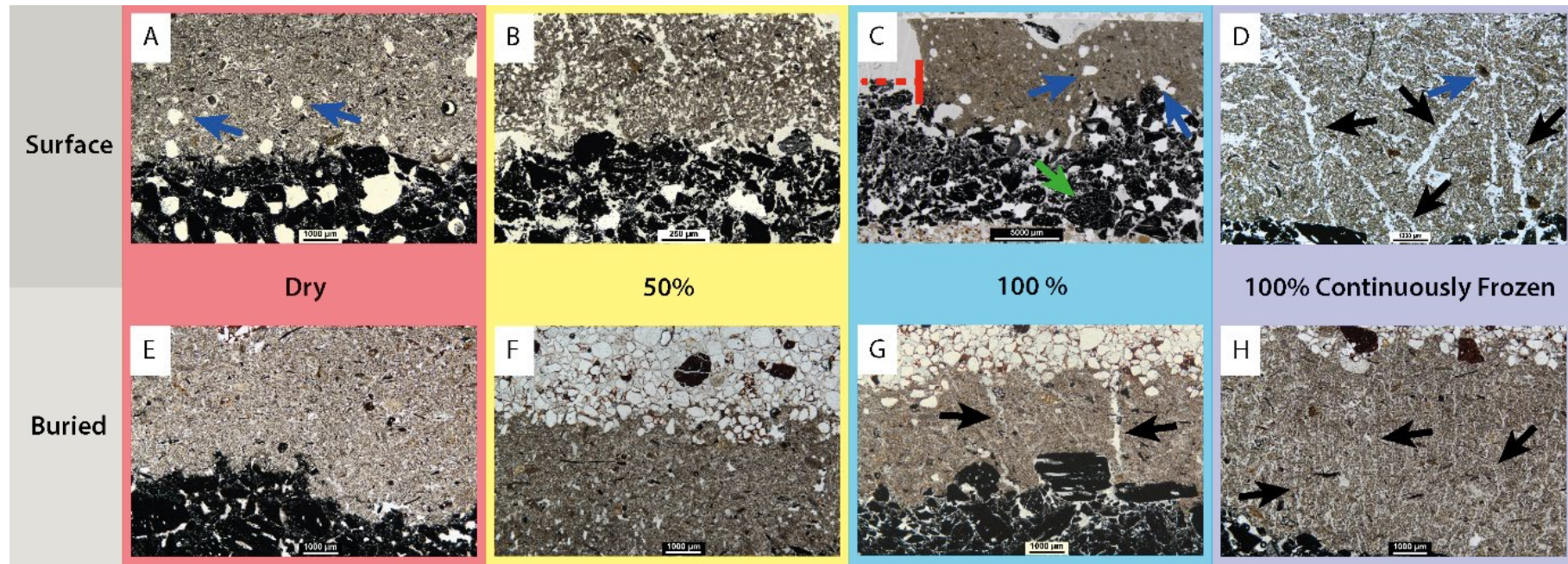


Figure 34: Photomicrographs showing the variability in frozen surface (A – C) and buried (E – G) ash layers based on moisture content after 60 cycles and ash layers that were continuously frozen (D and H). A) The dry surface sample has a generally massive microstructure with few vesicles (blue arrows) Scale is 1000, μm in PPL. B) Pillowly microstructure of surface ash layer with 50% moisture content. Scale is 250 μm , in PPL. C) Surface ash layer with 100% moisture content after 60 cycles has a very dense and massive microstructure with very few vesicles (blue arrows). The green arrow indicates possible frost cracked charcoal fragment. Note the gap in the ash layer indicated by the red dashed line. Scale is 5000 μm , in PPL. D) vertical and spiralling voids (black arrows) forming around vughs within surface ash layer continuously frozen single cycle, 100% moisture content. Scale is 1000 μm , in PPL. E) and F) are dry and 50% buried ash layers, both of which have generally dense massive microstructures with a few vughs. Scale for both figures is 1000 μm and both are in PPL. G) Buried ash layer with 100% moisture content has clear vertical planar voids. The layer is densely packed with a complex microstructure, scale is 1000 μm , PPL. H) The continuously frozen buried ash layer has dominant vertical planar voids throughout the complex microstructure. Scale is 1000 μm , in PPL.

Buried samples

In contrast to observations from the surface samples, there was no clearly developed lenticular structures in the experimental substrate visible within the thin sections of the buried ash and charcoal layers, and this is true regardless of the number of cycles (0,1,10,30, or 60) (Figure 35). However, like the surface samples, clay aggregates within the substrate show weak to moderate fractures visible in the 30 to 60 cycles

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samples (Figure 35). There was no discernible mixing between the experimental substrate and the combustion materials, though weak progressive mixing was observed of ash into the charcoal layer. This is apparent from the first cycle onwards, becoming more common by the cycle 60 (Figure 35).

Considering the ash and charcoal layers, the effects of repeated freeze-thaw on the charcoal layers are not clear from the microscopic perspective – like what we observed for the surface samples. In the ash layers, however, vertical cracks are visible after 10 cycles and are moderately developed after 60 cycles as shown in Figure 34 G. Within the single cycle samples frozen for 1290 hours, the vertical cracks are more extensive and visible throughout the ash layer. (Figure 34 H). However, it should be noted that vertical cracks were also present in the fully saturated sample kept at room temperature (Figure 32 F). No cracks were identifiable in the dry and 50% saturated samples (Figures 34 E and F). The microstructure of ash layers in the buried samples are generally massive.

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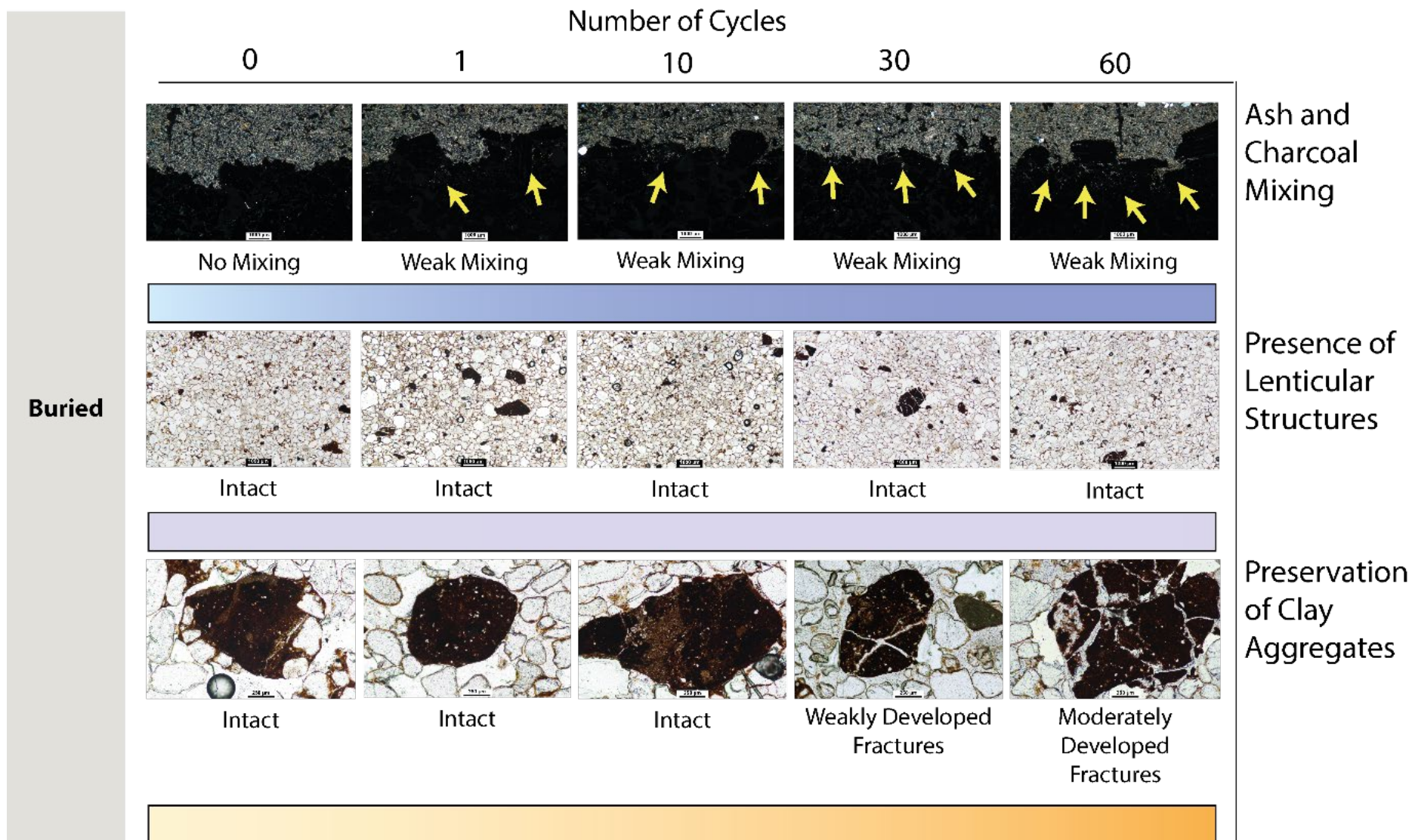


Figure 35 : Summary of the microscopic changes within the experimental buried samples based on the increasing number of cycles. The photomicrographs shown above were shot in XPL and PPL and at various scales shown in the pictures above.

5.4.3. μ XRF elemental mapping

Figure 36 shows the results of our μ XRF elemental mapping of the fully saturated experimental features from 0 to 60 cycles. For the surface samples, there is a clear progression of weakly developed lenticular structures visible (white arrows) from the 10 cycles onwards. No lenticular structures are visible in the buried samples. The development of mixing of the ash into the charcoal layer is clearly detected in the 30 and 60 cycles of the surface samples (yellow arrows in Figure 36). In contrast, the mixing between the ash and charcoal is apparent in the buried samples even after the first cycle (Figure 36). This mixing becomes more strongly developed around 60 cycles.

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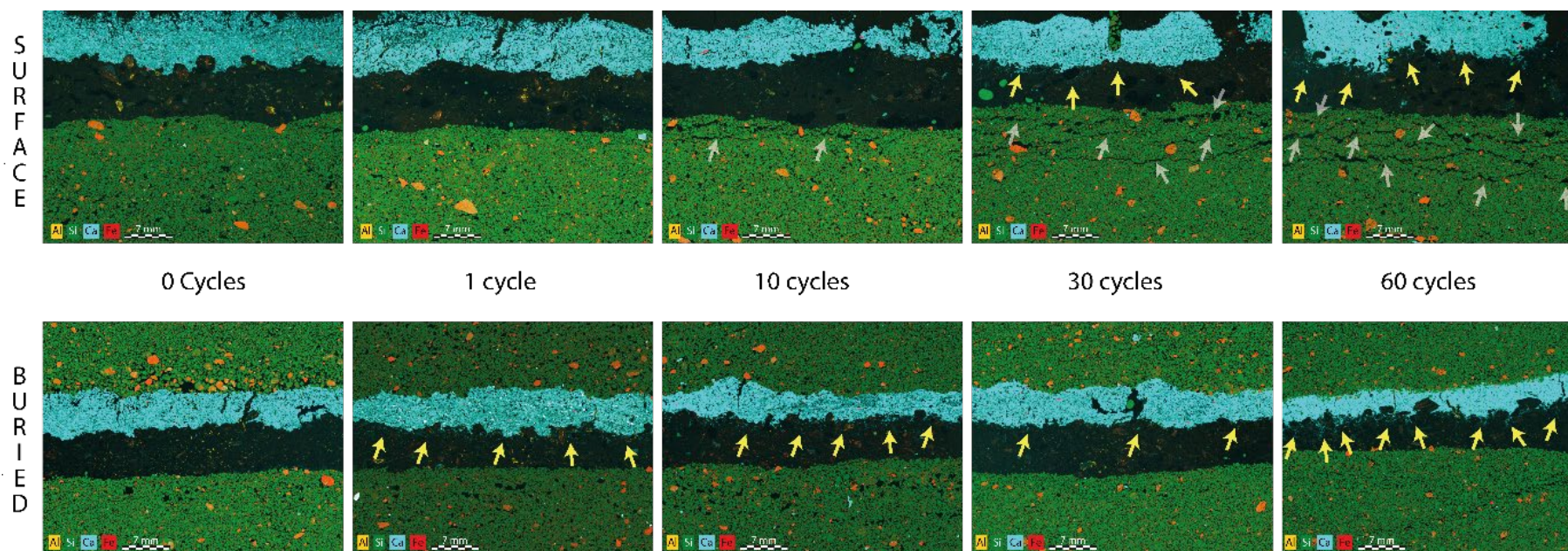


Figure 36: Summary of μ XRF elemental mapping for the fully saturated surface (upper series) and buried (lower series) after 0, 1, 10, 30, and 60 cycles. Elements depicted in the figure are the most representative elemental components for the clays (Al and Fe), Sand (Si), and ash (Ca). Note how the clay aggregates are easily detected (orange colour) throughout the experimental sediments. Porosity, namely the progressive development of lenticular structures, is clearly discernible in the surface samples from 10 cycles onwards (white arrows). The mixing between the ash and charcoal layer is indicated by the yellow arrows. Scale for all images is 7 mm.

5.5 Discussion

5.5.1 The effects of freeze thaw in the experimental contexts

The developed experimental design allowed for a standardized method of testing and examining the effects of repetitive freeze-thaw on combustion residues. Although the number of cycles we simulated was limited, our experimental design clearly demonstrated the development of freeze-thaw related internal structures and the relatively limited impact of these processes on sedimentary artifacts like combustion residues. Our combined results from statistical analysis, micromorphology, and μ XRF elemental mapping show that, with an increasing number of cycles, moisture content, and the position of the ash and charcoal layers are the defining factors for modification of combustion residues.

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The results from our statistical analysis consistently show that the surface ash treatment was statistically significantly altered: the ash layers decreased in averaged thickness and became more irregular as a factor of increasing number of freeze-thaw cycles (Figure 29 A and B) and moisture content within the sediment (Figures 27 A and 28 A). This decrease in thickness is visible in the micromorphological and μ XRF elemental mapping as the internal microstructure of the ash layers become denser and more massive as the number of cycles progress (Figures 32 C and 34 C). However, the increase in irregularity should be interpreted with caution. The disruption of the layer (areas with missing ash shown in Figure 34 C) is likely the result of unintended condensation build-up or water reprecipitation on the film used to cover the cylinder. As shown in the micromorphological and μ XRF analysis, the surface ash layer (100% moisture content) has a very dense and massive microstructure with portions of the ash layer missing (Figure 34 C and Figure 36). The other significant result from the macroscopic analysis is the increase of thickness of the surface charcoal (Figure 27 B), which appears to be linked directly to the moisture content with the charcoal fragments absorbing the water from the underlying substrate. This was not directly visible in the sample take for micromorphological and μ XRF sampling, however the absorption of water seems to be the most parsimonious explanation for the variation we detected statistically.

From a macroscopic perspective, the buried ash and charcoal layer are relatively unaffected by repetitive freeze-thaw. Similarly, there was no statistically significant change based on the duration of a single cycle, regardless of how long the sample was frozen. Changes between the layers was only detectable after the micromorphological and μ XRF analysis (Figure 36 and 37). As shown in Figures 33, 34, and 36 there is a weak, yet progressive, mixing at the microscopic scale between the ash and charcoal layers in both

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the buried and surface samples. As stated above, mixing between layers in the buried samples was detectable after the first cycle (Figures 35 and 36); while in the surface samples mixing is only visible around 30 cycles onwards. This suggest that the mixing of the ash and charcoal in the buried samples were enhanced by movement of water during freeze-thaw in the overlying saturated substrate. Mixing was not visible in the zero-cycle sample (100 % moisture content), so the mixing was not a product of our assembly protocol.

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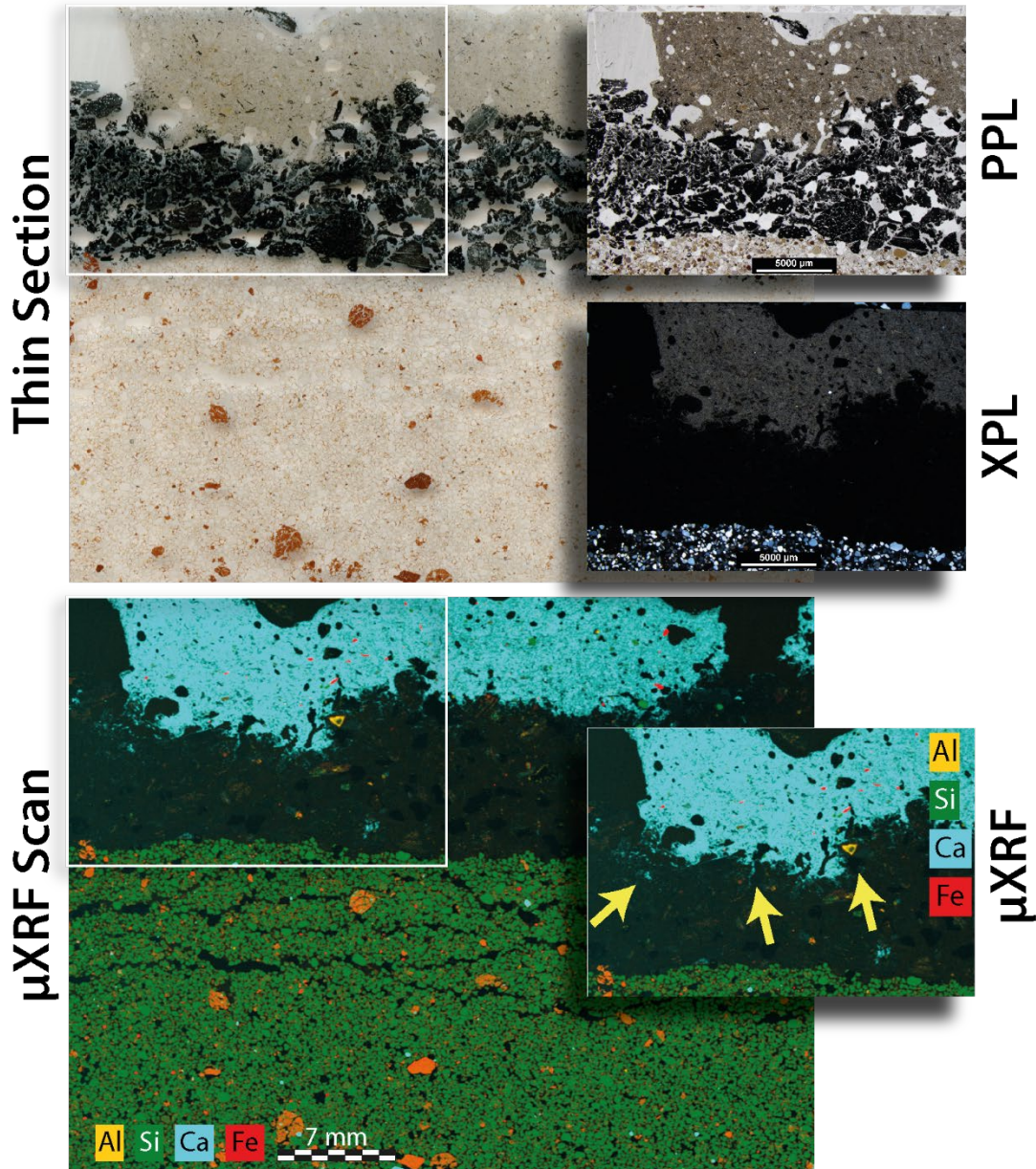


Figure 37: Diagram highlighting how the use of the μ XRF elemental mapping analysis can help improve the quality of the micromorphological analysis. This figure shows a portion of the thin section and the μ XRF scan of the surface ash and charcoal layers (100% moisture content) after 60 cycles. The mixing between the ash and charcoal layers is only partially detectable in XPL but is very clearly shown in μ XRF scan in the same location.

The progressive development of lenticular structures in the surface samples, compared to the lack of such structures in the buried samples, was likely due to the

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availability of water within the substrate. In Figure 23, we outline the process in which ice lensing forms within a substrate. As summarized by Van Vliet-Lanoë (1985), substrates with high moisture content tend to continuously form single surface lens rather than progressive lenses. Based on our results, we can suggest that the lack of progressive lensing in the buried samples is due to an abundance of water in the overlaying substrate. In the surface samples, it is likely that the absorption of water by the surface ash and charcoal created a moisture deficit conducive for ice nucleation in the underlying substrate. Ice lensing was also visible in the 60-cycle sample with 50% moisture content, albeit very weakly developed. No ice lensing was visible in the dry 60 cycle sample, which is consistent with the findings by Van Vliet-Lanoë (1985).

Overall, the results of our study suggest that combustion residues, such as ash and charcoal, are very robust and resilient to repeated freezing and thawing as an isolated process. Apart from the surface ash layer, there was very little alteration in terms of thickness and regularity of the surface charcoal and buried ash and charcoal. The modification of the regularity of surface ash layer is – to an extent – an artifact of our experimental design since we elected to use a closed system in which the experimental cylinders were covered. This resulted in condensation of water during the thawing periods and the subsequent dripping of water on top of the exposed surface ash layer. However, if we consider the presence of a real combustion feature left exposed on a surface, the effects of either rain in open air sites or water dripping from a ceiling in cave sites could, theoretically, result in the same physical disruption of the exposed ash layer. Still, and apart from this decrease in thickness, overall, the surface ash layer is relatively intact. The ash residues are well preserved even at the microscopic scale, with little or no dissolution even after 60 cycles of freeze-thaw. This level of intactness of the combustion residues is

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particularly true for the buried residues. This evidence suggests that a) rapid burial is significant in terms of preservation of combustion remains, and b) the physical modification and/or redistribution of combustion residues by freeze-thaw is negligible under our experimental design. This suggests that significantly more repetitions of freeze-thaw than simulated here are needed to disrupt combustion residues and/or loss of such residues relies on a combination of several other processes over time. While the first conclusion that a rapid burial equals better preservation is not groundbreaking (Renfrew & Bahn, 2013), here we have provided a measurable and repeatable results validating it and for the first time applied to the preservation of combustion remains experimentally. Secondly, our results clearly show combustion remains stay relatively intact and in place after 60 freeze-thaw cycles. The fact there is no mixing of ash and charcoal remains into the underlying substrate is significant as there is clear ice lensing in the surface samples and the fragmentation of clay aggregates in both the surface and buried samples. This result might vary based on the composition of the underlying substrate but likely not by a significant amount. While further experiments will be needed to simulate more cycles, our experiment effectively demonstrates that freeze-thaw has a generally limited effect on the preservation and identification of combustion remains after 60 cycles.

While our experimental setting allows to discern some effects on freeze-thaw cycles on combustion residues, we should point out that there were some limitations to our study. Firstly, albeit with some differences in levels of development, width, and abundance, we observed the presence of vertical cracks in various samples with 100% moisture content. These include buried samples that underwent 60 cycles (Figure 34 E), both the surface and buried continuously frozen samples (Figure 34), as well as the buried 0 cycle sample kept at room temperature (Figure 32 D). In the continuously frozen

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samples, the cracks in the surface ash layer are well developed and appear to radiate from vughs. The buried 60 cycle and the buried 0 cycle sample also have well developed cracks albeit more vertical than in the continuously frozen surface sample. Meanwhile, the buried continuously frozen ash layers have hundreds of small vertical planar voids or cracks. The presence of vertical cracks in the buried 0 cycle ash layer could suggest that these porosity structures are a result of desiccation from the absorption of water from the experimental substrate rather than directly related to freeze-thaw cycles. However, this result is isolated to only one sample and not present in any of the other treated samples at room temperature or any other samples other than the ones listed above. As such, it is likely a product of the protocol rather than a significant result. Additionally as our design did not vary the composition of our substrate, ideally further experiments should be conducted using potentially various grain sizes and textures (Van Vliet-Lanoë, 1985, 2010). Future experiments should be conducted potentially varying the availability of water to simulate more natural conditions (Henry, 2007). Furthermore, we also did not vary the surface tilt or slope in our experimental design. The addition of slope would likely influence any potential redistribution of the combustion materials as seen in experiments on other materials (Bertran et al., 2015; Lenoble et al., 2008; Masson, 2010; Texier et al., 1998) and should be examined in further detail. As stated above, further experiments should also focus on simulating a higher number of cycles over a longer period.

5.5.2 Archaeological implications:

Our results have clear implications for archaeological interpretations for studying anthropogenic fire use. Firstly, we can conclude that the lack of combustion remains

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during glacial periods during the Pleistocene (Abdolazadeh et al., 2022; Dibble et al., 2017; Dibble et al., 2018b; Murphree & Aldeias, 2022) cannot be explained away as a result of simple freeze-thaw related processes. This does not negate other processes that could have attributed to the lack of preserved combustion remains during this period – namely periglacial conditions involving processes of frost jacking and solifluction, (see for instance Masson (2010)). Archaeological deposits are a product of a dynamic continuous system of different geogenic, anthropogenic, and biogenic processes taking place both concurrently and independently of each other (Binford, 1981; French, 2005; Goldberg & Berna, 2010; Goldberg & Macphail, 2008; Schiffer, 1972, 1987). However, as shown in the case study presented in chapter 4, the LGM combustion features at Korman'9 are still relatively well preserved even when subjected to repetitive freeze-thaw as well as other frost related processes (namely solifluction). This would suggest that if fire was being used by humans, then a distinct signature (such as presence of charcoal and red layers) would be expected to be preserved even in periglacial environments.

Secondly, given the overall good preservation of charcoal-rich layers, our results suggest we cannot assume the presence of charcoal in association with material culture is anthropogenic. Fire and combustion are natural processes that can occur independently of human agency. Isolated charcoals or charcoal clusters are commonly found in association with archaeological remains, and - as shown in chapter 3 - are interpreted as anthropogenic due to the lack of clear natural sources (Murphree & Aldeias, 2022).

However, these experiments show that combustion layers are extremely difficult to erase completely. This is not to claim that fire should be preserved at all sites throughout time, but archaeologist should approach claims of fire use based solely on the presence of charcoal or other combustion related remains with caution.

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Overall, the potential lack of anthropogenic fire use during glacial periods poses intriguing new questions about human behaviour. Many of which have been obscured by our generalized views of hominin fire use and blanket assumptions regarding the necessity of fire for as a survival tool in cold environments (Chapter 2). If modern humans and their ancestors were not dependent on fire in glacial conditions, then what other adaptations did they have to survive in cold periods? We need to pose new questions of how we can detect these behaviours in the archaeological record and what new tools and techniques can we develop to fill this gap in hominin evolution. Finally, this demonstrates the need to conduct detailed multiscale studies of site formation processes at different sites. It also highlights complexity of the archaeological record and brings into question how we infer behaviour and make generalized interpretations of past behaviours.

5.6 Conclusions

Our aim with this experiment was to simulate the effects of repetitive freeze-thaw on the preservation and recognition of combustion remains. The driving motives behind this experiment laid in the peculiar pattern observed of lack of well described combustion features in association with cold glacial conditions during the LGM (Murphree & Aldeias, 2022) and the reported lack of fire use during cold periods in association with Neanderthal occupations in SW France (Dibble et al., 2017; Dibble et al., 2018b). Therefore, this experiment focusing on the degree of preservation of combustion residues (ash and charcoal layers) is a first step helping to fill a current gap in how we interpret archaeological combustion remains in the Eurasian Pleistocene archaeological record. With this in mind, we conducted a controlled experiment where we varied the position of

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subsequent experimental treatments of ash and charcoal layers as well as the number of cycles and amount of water within the substrate. We then analysed our results using multiscale analytical techniques including micromorphology, μ XRF elemental mapping, and statistical analysis of macroscopic measurements. Our results showed that freeze-thaw has only a very limited effect on combustion residues preservation even when exposed to 60 freeze-thaw cycles. In our experimental results, only surface ash layer showed statistically significant decrease in thickness and increased irregularity. In addition, we were able to identify weak progressive mixing of the ash into the charcoal layers, as well as the progressive ice nucleation in the surface samples as the number of cycles increased by using combination with micromorphological analysis and μ XRF mapping. While further experiment work is needed to expand the experimental variables (e.g., extended number of cycles, distinct substrates and moisture contents), our experimental design allowed us to show that, in a controlled setting, combustion residues are resistant to freeze-thaw cycles, maintaining their composition and their stratigraphic integrity, particularly when buried. It also highlights the strength of integrating multiscale investigative techniques to study the remains of anthropogenic fire use. These results can have further reaching implications in how we interpret past behaviours and perceived lack of evidence in archaeological settings. Moreover, our simple base design can be further adapted to study the effects of freeze-thaw on other materials such as biomarkers and sedimentary DNA, something currently lacking in Paleolithic archaeological research (Aldeias & Stahlschmidt, 2024).

Chapter 6

6.0 Discussion

6.1 Patterns in Upper Palaeolithic fire use

Chapter 3 shows that the overall published record for pyrotechnology in the Upper Palaeolithic is sparse but has unique behaviour patterns that have not been seen in other periods within the Eurasian Pleistocene record (Murphree & Aldeias, 2022). In this section, I will further expand on some of the discussion points mentioned in Chapter 3, while integrating perspectives and results from the subsequent Chapters 4 and 5.

Throughout Chapter 3, we tried to separate, when possible, combustion features from their associated technocomplexes by using more neutral or less biased terms like initial (IUP) or early Upper Palaeolithic (EUP). This was not always possible and, in many cases, the interpretations we made are based on generalized patterns of behaviour. With that said, there are key underlying patterns throughout the Upper Palaeolithic, regardless of their interpretive associations with lithics technocomplexes.

Our findings from the IUP generally mirror fire use by late Neanderthals *vis-à-vis* the use of simple flat hearth constructions (Aldeias et al., 2012; Allué et al., 2022; Leierer et al., 2020; Leierer et al., 2019) and isolated cases of the use pit structures (Leierer et al., 2020; Marcazzan et al., 2022; Murphree & Aldeias, 2022). The use of pit structures becomes more widespread in the EUP with several of these features found in sites in southwest France and western Europe (Braadbaart et al., 2020; Movius Jr, 1966; White et al., 2017). Additionally, the EUP also features the first clear evidence of prepared surface structures in

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Greece (Karkanas et al., 2004). In Chapter 3, we suggest this is potentially evidence for regionalisation of pyrotechnology (Murphree & Aldeias, 2022).

The importance of recognizing potential regionalisation is two-fold. Firstly, it shows that groups using similar stone tools (e.g., Aurignacian) are approaching constructing fire (and potentially using it) in different ways. As stated in Chapter 2, fire use has its' own constraints and limitations, which are unique compared to other forms of technology. In the case of regional differences, we can see that populations are developing and using this technology in unique ways, regardless of the perceived similarities between stone tool types. This highlights the need, at the very least, to separate pyrotechnology from other tool types in human behaviour. Secondly, regionalisation also highlights that the use of pyrotechnology should not be considered a universal modern human adaptation. The differences identified between one group using a certain type of structure and another group with a distinct structure indicates that fire use is not "one size fits all" adaption. The structural variation between these regions could be due to environment, resource availability, fire use traditions, social organization, or a variety of other behavioural adaptations. It also could be due to function. While generally the function of combustion features is unclear, it is nonetheless possible that the structural variation between western Europe vs Greece could represent different adaptations of fire use to similar ends. Vice versa, the structures could have completely different functions - for now, we cannot state for sure. However, it is possible that the regionalization of pyrotechnology during the same period of so-called "pan-European technocomplexes" highlights some of the complexity of the Upper Palaeolithic record. This regionalisation is also a clear precursor to what could be considered a major transition in the evolution of pyrotechnology.

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This transition from early to middle Upper Palaeolithic (MUP) likely represents a major turning point in how humans used and adapted pyrotechnology in their behaviour (Murphree & Aldeias, 2022). This change in technology is generally associated with the spread of the Gravettian technocomplex throughout Europe. Regardless of the lithic association, however, there is a clear change in the morphology of fire features, including the diversity of structure types, shape, size and form, especially in central Europe (Murphree & Aldeias, 2022). This includes the first potential instance of a fire installation, or the so-called kiln-like structures from Dolni Věstonice I (Svoboda et al., 2015; Svoboda et al., 2018; Vandiver et al., 1989; Verpoorte, 2000). MUP combustion features also show increased intensity of use over long periods of time (Murphree & Aldeias, 2022), some of which potentially were used year-round (Beresford-Jones et al., 2010; Pryor et al., 2016). Moreover, there is the first instances of ceramic technology with baked clay and loess artifacts in the archaeological record (Farbstein & Davies, 2017; Vandiver, 2022; Vandiver et al., 1989; Verpoorte, 2000; Vlačíky et al., 2013). As stated in Chapter 3, this likely represents a shift in fire related behaviour from exploiting fire as a natural resource towards a cultural resource (Chazan, 2017; Murphree & Aldeias, 2022). The development of these behaviours can be linked to a change in mobility patterns from highly mobile hunter gathering groups that characterized the majority of the Pleistocene to near semi sedentary occupations, at least in the Middle Danube and Moravia regions of central Europe (Beresford-Jones et al., 2010; Kozłowski, 2015; Pryor et al., 2020b; Pryor et al., 2016; Svoboda, 2007). In other parts of Europe, the record is less clear. For instance, many of the innovations seen in central Europe are not visible in western Europe (Belmiro et al., 2020; Haws et al., 2020; Movius et al., 1977). Meanwhile in eastern Europe, similar structures to the Moravian and Middle Danube regions (that is, pit and prepared surface features) have

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been found at Kostenki-Borshevo sites in Russia (Hoffecker & Anikovich, 2014; Lisitsyn, 2015; Pryor et al., 2020b; Sinitzyn & Sanz, 2015; Zheltova, 2015). It should be noted that much of the evidence from Moravia and the middle Danube region, as well as from the Don River basin in Russia, are from open-air locations, while much of the western European record is derived from cave sites. However, the reason for the lack of diversity in types of combustion features in the West is not completely clear.

The shift in fire use in the MUP could arguably be the first definable period in the Upper Palaeolithic where fire use was obligatory in the behaviours of certain populations. Obligate or habitual fire use, as defined by Shimelmitz et al. (2014) and later Sandgathe (2017), is when fire use is a "regular" or "persistent" part of human behaviour. Prior to the MUP, the evidence of fire use is – I would argue - sporadic. While there is evidence of repeated use of fire at certain sites, none share the same intensity of use, showing a variety of structures at the same site and the presence of non-utilitarian baked objects, all within the same region and similar time frame. This statement by no means dismisses or diminishes the significance of use of fire by modern humans in early periods. In this distinct region of Moravia and middle Danube these groups or populations have a clear definable dependency on fire on an arguably daily basis. At the very least the evidence suggest that fire use was important to the social structure and behaviours of these groups. The evidence also suggest that combustion features were created to be standardized functionally. In other words, groups constructed certain structures with a particular function in mind, in order, for instance to control the properties of heat from multiple dimensions or to increase firing temperatures to harden objects like ceramics. It remains unclear if the same can be stated for other regions. It is clear however, that these behaviours did not continue in later periods, as we will further discuss below.

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Another key finding from Chapter 3 is the lack of well described combustion features from 26 to 19 ka BP, which corresponds to the LGM. While our case study from Korman' 9 in Chapter 4 provides insights into this gap, the key takeaway from this study is that some human groups used simple flat hearths, with no clear evidence of reuse during the LGM. When compared to relatively contemporaneous sites in the region, the general trend appears to be the use of simple flat hearth structures, some of which were with or without linings (Chernysh, 1977, 1987; Noiret, 2009). As stated in Chapter 4, these features are not described in detail. The findings in Chapter 4 only represent a single region of Europe. The rest of the European record for the LGM is severely lacking data, with only a few publications of sites mentioning the presence of combustion features (Chapter 3). This is in clear contrast to earlier MUP period, where there is more diversity and intensive use of fire. As such, it is possible that resource and environment stresses changed the investment strategies of humans in terms of fire use and mobility. It can then be hypothesized that groups gradually switched to more practical and functional structures to reduce time and resource expenditure in construction and maintenance.

During the LGM, mobility patterns appear to become more ephemeral, with groups continually moving from one place to another to avoid prolonged resource stress. There are several examples throughout later periods of history where climate change has had a drastic effect on human behaviour and settlement patterns. While these are not truly analogous, the collapse of agricultural societies like the classical Mayan and Indus valley civilizations has widely been attributed to resource stress due to climate change (Dixit et al., 2014; Haug et al., 2003). While it is generally assumed mobility in hunter gather communities would make them more resilient to regional resource stress (Bicho & Cascalheira, 2018; Bicho et al., 2019; Bradtmöller et al., 2012; McLaughlin et al., 2021),

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climate change on a global level such as the LGM could have had a drastic change on human behaviour and adaptations. In effect, these groups had to adapt to living in glacial and periglacial conditions, featuring extreme cold and aridity, during a millennial time scale.

The use of short-lived simple flat hearths alone cannot explain the lack of well described combustion features from the LGM. In Chapter 3, three possible reasons were proposed for the lack of these features during the LGM (Murphree & Aldeias, 2022). These include publication bias, absence or limited use of fire due to resource stress or a lack of preservation due to freeze-thaw related processes in periglacial environments (Murphree & Aldeias, 2022). In Chapter 5, we concluded that freeze-thaw alone cannot account for the lack of combustion features in periglacial environments. While limited in the number of simulated cycles, our study showed little to no change to the internal structure and preservation of ash and charcoal residues. While this does not exclude other processes influencing preservation, freeze-thaw alone likely takes thousands if not tens of thousands of cycles to disrupt the signatures of combustion. Furthermore, this study showed that, once buried, combustion remains are very well preserved. We therefore concluded that combustion features are extremely difficult to erase completely. This is supported by the results from Chapter 4, where combustion features from AL 1 at Korman'9 are relatively intact even with extensive evidence of cryoturbation.

In summary, it is possible the LGM had a winnowing effect on human behaviour, in which adaptations to extreme cold cause the selection of simple flat structures or other non-fire related adaptation. It is likely that the cost of fire, in terms of its resource intensity and stress on social organization, outweighed its benefits during the LGM. In which case, humans had to depend on other adaptations and behaviours to survive (Speth, 2017). This

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brings to question whether fire was important to humans in the Upper Palaeolithic as we assume it would be. If this is not the case, then the diametric relationship we use comparing Upper Palaeolithic modern humans and earlier hominins is a base rate fallacy. This means it is likely that the importance of fire is overestimated based on its prevalence on few sites rather than accounting for all the data available.

The post-LGM fire use record is again more regionalised compared to the MUP and LGM (Murphree & Aldeias, 2022). However, unlike the regionalisation in the EUP, the post LGM European landscape features several different regionalized lithic technocomplexes. For instance, the Solutrean in southwestern Europe, the Magdalenian in western Europe and parts of central Europe, and the Epigravettian in central and eastern Europe. In western Europe, several sites feature wide range of combustion structures, including simple flat hearths, pit structures, and prepared surface structures (Bergadà et al., 2013; Fullola et al., 2012; Nakazawa et al., 2009). Many of which show intensive reuse and restructuring (Murphree & Aldeias, 2022). In central and eastern Europe, the record still suggests a predominance of simple flat hearths (Murphree & Aldeias, 2022). The regionalisation of pyrotechnology in the LUP might have a similar mechanism to that of the EUP, where geographic isolation of different populations leads to the development of different fire use traditions. It also could be the result of resource stress, mobility dynamics or simply site location. As mentioned above, most of the evidence from western Europe came from cave sites, while in eastern Europe is predominantly open-air sites.

Perhaps what was the most striking result from Chapter 3, is the general scarcity of well described combustion features in Upper Palaeolithic sites throughout Europe. In our paper, we presented data from 164 different sites dating between 48,000 and 13,000 years ago. Of these, 109 out of 164 sites mention fire being present with no further description.

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Only 55 sites had some descriptions of individual features at a macroscopic level, and of these only 11 have detailed multiscale analysis. While it was not possible to access or assess every publication that mentions fire use, this literature review does reveal how limited the available data on Upper Palaeolithic combustion structures is currently.

Moreover, our focus in the review paper was on finding positive evidence for fire use and collect data on combustion structures. We did not look for how common sites are with no fire features in the Upper Palaeolithic record. This “invisible” record is likely heavily obscured by our generalized views of modern human behaviour and generations of positivistic interpretive narratives when it comes to missing evidence of behaviour (assuming the lack of features are a product of poor preservation or sampling). Both are explored in more detail in the next section. In conclusion, while we were able to identify patterns of behaviour based on limited datasets; we are arguably blind to the amount of variability that might exist in Upper Palaeolithic fire use behaviours and lack thereof in individual group behaviour.

6.2 The “invisible” record of non-fire use

Our current research paradigm for interpreting the evolution of pyrotechnology in the Palaeolithic of Europe is commonly based on a diametric comparison between limited but progressively increasing evidence of fire use in the Middle Palaeolithic and the assumed ubiquitous use of fire by modern humans in the Upper Palaeolithic (Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011). While I have shown that the evidence for pyrotechnology in Upper Palaeolithic is still relatively scarce, another point to consider

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is the potential “invisible” record for adaptations for survival in cold conditions without the use of fire.

This subject is regularly absent from the current research and prompts new questions about how we interpret the development of anthropogenic fire use. At what point can we suggest that evidence of anthropogenic fire use is absent in an archaeological site? What does that mean for how we interpret past human behaviour? Conversely, on sites where fire is present, how prevalent is it? Are there gaps in record where there are occupational materials but no fire or vice versa and how prevalent is fire use in comparison to occupational intensity?

Sites with clear evidence of being without anthropogenic fire are likely extremely difficult to identify in the current literature. Moreso, the general assumption is that fire use is an essential part of modern human and Neanderthal behaviour for living in cold environments. The lack thereof at some sites has been explained as due to a lack of preservation, ephemeral and/or small scale fire use, site organisation, or sampling error/size (Sorensen, 2017). Moreover, many authors point to the presence of indirect proxies, like burned lithic fragments and charcoal concentrations, or so called “fire starters”, as positive evidence for fire where combustion features are missing (Abdolahzadeh et al., 2022; Alperson-Afil, 2008, 2017; Dibble et al., 2017; Dibble et al., 2018b; Sorensen et al., 2014; Sorensen, 2024; Zohar et al., 2022). Archaeologists are focused on finding positive evidence of fire use, therefore they are likely ignorant to outliers with evidence of no fire use. However, sites with no evidence of fire use and their context should be considered before creating interpretive frameworks describing the evolution of pyrotechnology in human evolution.

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In this thesis, I have shown that, in specific contexts, the evidence of fire use is extremely hard to erase completely (Chapter 5). We have also identified that descriptions of Upper Palaeolithic combustion features tends to be sparse and to vary significantly. Throughout much of the available literature, the descriptions and definitions of fire use or combustion features differ substantially in terms of describing morphology, characteristics, or implying function (Goldberg et al., 2017; Mentzer, 2014; Murphree & Aldeias, 2022). The lack of clear descriptive standards or the potential for misidentification of natural vs anthropogenic derived combustion remains, especially on older sites or sites with significant post depositional alterations (Marquer et al., 2012; Nejman et al., 2018; Stahlschmidt et al., 2015), could lead to an overestimation of the prevalence of anthropogenic fire use in the archaeological record. This is not to outright dismiss all claims of fire use from earlier excavations, outdated methods, or historical descriptions of combustion features, but such evidence should be approached critically and analysed to the same standards applied to other material culture (Dibble et al., 2016; Dibble et al., 2018a; Dibble et al., 2009). Combustion features are sedimentary artifacts, which once excavated is lost forever. As a result, it is not possible to reexamine the evidence of combustion features beyond the descriptions given by archaeologist at the time. When comparing the overall record of fire use with our assumptions about its prevalence; one wonders why fire use is not more frequently documented in the published literature.

Another question regarding the “invisible” record that should be asked is how prevalent combustion features are within archaeological occupational horizons or levels? Occupational horizons, as summarized by Dibble et al. (2016), can be products of multiple different visits by unrelated groups taking place over hundreds of years. Therefore, it could be hypothesized that if fire was an essential part of daily life, then the signature of fire

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should be very abundant and visible in sites with thick occupational horizons. Yet, this is not always the case in the archaeological record. For instance: at the French site of Quinçay, two intact combustion features were identified by the original excavators and tentatively associated with Mousterian occupations at the site (Lévêque, 1979; Lévêque et al., 1993; Lévêque & Miskovsky, 1983). However, the site has multiple subsequent occupations with no intact evidence of combustion (Lévêque & Miskovsky, 1983; Roussel & Soressi, 2010b). Another example is the site of Willendorf II, in Austria, which has multiple Upper Palaeolithic occupations starting around 43,500 years before present, yet it has no identifiable combustion features present in the excavated sections (Nigst et al., 2014). The Upper Palaeolithic site of Pod Hradem, in Czechia, also has no evidence of anthropogenic fire use but has multiple occupation horizons (Nejman et al., 2018). It is likely there are many more examples in the current literature that are currently being overlooked as they are viewed as outliers rather than fitting our normalised assumptions of fire use.

Equating occurrence of fire and thickness of occupational horizons has three main issues. Firstly, the direct association between the use of fire and other material culture within an occupational horizon is a product of archaeological interpretation. We assume relatedness between behaviours due to their proximity, where they may completely unrelated (Dibble et al., 2016; Sandgathe et al., 2011). A recent paper on the timing of between hearths at the site of El Salt (Spain) by Herrejon-Lagunilla et al. (2024) showed in some cases decades long hiatuses between the use of superimposed hearths with the entire studied sequence forming over 200-240 years. Secondly, there is no clear consistency on how occupational intensity is assessed and reported, and how would that be reflected in the fire use (Dibble et al., 2016; Sandgathe, 2017; Sandgathe et al., 2011). Can we assume that thickness of the red and black layers of a combustion feature has a

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correlation to other behaviours taking place around it? How does stacking and the superimposition of combustion features correlate to the thickness of occupational intensity? Does the presence of superimposed or stacked features like those at Krems Wachtberg, El Parco, El Salt, or Kilsoura (Allué et al., 2013; Fladerer et al., 2014; Fullola et al., 2012; Händel et al., 2015; Herrejon-Lagunilla et al., 2024; Karkanas et al., 2004; Simon et al., 2014) represent reuse, refuelling, and maintenance by the same group over time or distinct groups using the same space like those seen in modern hunter-gatherer groups (Binford, 1978; Mallol et al., 2007; McCauley et al., 2020)? Do some of these groups occupying the site use the features and others do not? Finally, how we can compare intra-site and inter-site occupational intensity with different sedimentation rates? How does this influence the interpretation of occupation intensity and or the prevalence of fire use at for a site with high sedimentation rates compared to lower rates. Do low sedimentation rates obscure multiple occupations?

Many questions remain about a behaviour that we consider indispensable for survival in cold conditions. Overall, the potential for an “invisible” record is an intriguing prospect for future research and this not only in the Pleistocene archaeological record but also in the Holocene record as well.

6.3 The Prometheus Problem

Chapter 2 includes overview of the general state of the art regarding the theoretical framework used to interpret and codify fire use in the Palaeolithic of Eurasia. Based on what is known about Upper Palaeolithic fire use and its preservation in periglacial conditions, I would suggest that the current theoretical frameworks used to

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describe evolution of pyrotechnology might be conceptually accurate, but the scale, chronology, and generalized views we associate with it are flawed.

Firstly, fire use is likely not a species specific or commonly shared trait in the genus *homo*. Fire use could have evolved multiples times in individual groups or populations over tens of thousands if not hundreds of thousands of years (Sandgathe, 2017). The evolution of pyrotechnology was more than likely punctuated by several starts and stops or expansions and contractions. The development of pyrotechnology is likely a product of localized social and cultural adaptations, which developed based on environmental and resource constrains as well as access to natural fire sources. In theory, no individual species was the progenitor of fire use, nor was habitual fire use a commonality within a specific species (at least in the Palaeolithic context). In my view, the so called "invention" of fire use is probably an adaption, independently selected and maintained by different populations at various times when conducive for their survival and/or when natural sources of fire were available. It is also as likely that there are several groups and populations that did not use fire or only used fire sporadically. These groups potentially had different adaptations for living in cold environments or only used fire when it was readily available to them.

It is also likely that the prevalence of artificial fire starting was also more fluid and independently reinvented and lost several times. While fire starting might have become more prevalent in the late Pleistocene, it is possible it was not a universally shared technology at a species level. Similarly, the increasing complexity of fire use, such as construction of more standardized forms of structures to conform to a specific function, was inconsistent throughout the Pleistocene record and reflect behaviour adaptation by distinct groups and populations rather than a general ever-increasing trait.

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Throughout most of the Pleistocene, the record for fire use is very limited and sporadic in nature (Roebroeks & Villa, 2011; Sandgathe, 2017; Sandgathe et al., 2011). By attaching fire use to other forms of technology, vis-à-vis lithics (Chapter 2), we have created an overly generalized structure that ignores much of the diversity in pyrotechnology and overemphasizes the importance of fire on the biological and social evolution of the genus *homo*. This however does not diminish the capacity or capability of *homo* Erectus, Neanderthals, or any other hominin to use fire. I would argue it augments the innovative and social capabilities of these species to adapt to different climate conditions and landscapes in different ways.

So, when do we become dependent on fire use in the archaeological record? As “habitual” fire use would generally require the ability to create fire at will, there is likely not a clear threshold in context of the Palaeolithic period. It is possible that habitual fire use may not be sustainable for many populations due to cost and availability of fuels. The loss of which could be a long-term response to climatic change and resource volatility. I would argue that precursors for habitual fire use might have appeared in the MUP, but was effectively stopped by resource stress and climate downturn associated the onset of the LGM. Our now modern dependence on fire use and its’ various proxies started in the Holocene, possibly as a byproduct of resource intensive subsistence strategies like the advent of agriculture.

Overall, our interpretive models for understanding the evolution of pyrotechnology need to be more dynamic and not dependent on over generalized assumptions based on the presence of fire use in the archaeological record. Archaeological interpretations of fire use should also be considered independently of other material culture. These association have some utility in terms of giving a relative

chronological and potential spatial anchor for different behaviours depending on the context but are not necessarily intrinsically linked to one another. Furthermore, the development of anthropogenic fire use behaviour was by no means a linear progression through time. It was likely punctuated by several starts and stops and expansions and contractions of not only the usage of fire, but also the standardization of function by different groups and populations through the course of the evolution of the genus *homo*.

6.4 Limitations and future perspectives on fire use.

In this thesis, I have highlighted the need for more standardized descriptive methods for interpreting fire use in the archaeological record. I have also addressed the need for archaeologist studying fire use and building interpretive frameworks for the evolution of fire use to consider the “invisible” record of non-fire use. I have also proposed a new model for discussing and interpreting fire use behaviour in human evolution. With this said, I have built this perspective based on the geoarchaeological framework and by focusing on the structural evolution of combustion features. While this framework has many strengths, it also has limitations that I address below.

Firstly, it is necessary to be careful in over empathising typological definitions for the combustion features as an interpretational basis for understanding variation in fire use. Typological definitions can often be focused on the end or finished product, which, in the case of fire, are the shape of combustion features (Mallol et al., 2017). On one hand, typologies are useful in providing a comparative basis for understanding behaviour, while on the other it can introduce an interpretational rigidity in which the shape or morphology reflects a desired function or outcome. This can mimic the chaîne opératoire

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approach used on lithic analysis, which attempts to reconstruct the step-by-step approach to reach a desired product. The end product is based on interpretation and may not match the intentions of the people using lithics (Dibble et al., 2016). Fire use typologies could present the same limitations.

The use of typologies can also generate bias among the interpretation of patterns in pyrotechnology. For instance, the pattern of regionalization discussed in this Chapter and Chapter 3, could also be a biased product of the structural typology we used in our publication. The structural typology was based on commonly shared morphological characteristics (Mallol et al., 2017). As stated above, it is possible both structure types might be an end to the same means or function. However, considering that scholars cannot assume intended function of Palaeolithic combustion features, using this structural typology was the most appropriate metric for this study given the current (lack of) data available.

Secondly, we should strive to include more perspectives from other archaeological theoretical frameworks. Much of what is discussed in this thesis is rooted in processual and some post-processual archaeological perspectives, emphasizing the link between observable variations in inferred behaviour to environmental, biological, and social constraints. It also focuses heavily on site formation processes to validate and invalidate different interpretations and perspectives on fire use. Future studies, could consider other perspectives and theoretical frameworks from anthropology or biology.

Overall, this thesis provides new data and new perspectives on the use of pyrotechnology in cold environments during the Upper Palaeolithic of Europe. It also applies this data into the overall framework of how the Eurasian Pleistocene record for fire

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use is studied. Its goal was a springboard for future research into pyrotechnology and inform future interpretations on the evolution of fire use.

Chapter 7

Conclusions

This thesis focused on understanding how pyrotechnology, or the use of fire as a tool, developed and was preserved in periglacial environments during the Upper Palaeolithic of Europe. The objectives of this thesis were, first, to better understand how modern humans used and developed pyrotechnology in Europe and examine how it changed through time. Secondly, it was to see how the evidence of fire use is preserved in cold environments and how it was affected by periglacial conditions where freeze-thaw related processes dominate the landscape.

In Chapter 2, I outlined the theoretical perspectives that frame how pyrotechnology is studied. I also provided a critical assessment of the current state of the art for the evolution of fire use in human evolution. Here, I showed how the use of generalized patterns of behaviour has limited our ability to identify outliers in fire use behaviours. I also highlighted some of the commonly overlooked issues and problems such as the cost of fire, the association of combustion features and other material culture, and the lack of preserved fire-starting tools in the archaeological record. I also highlighted some of the existing assumptions regarding Upper Palaeolithic fire use and what they imply.

In Chapter 3, I presented our review paper, Murphree & Aldeias (2022), which looked at the structural evolution of pyrotechnology in the Upper Palaeolithic of Europe. In this paper, we identified several patterns in modern human fire use. Firstly, the potential regionalisation of pyrotechnology in the early part of the Upper Palaeolithic (Murphree &

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Aldeias, 2022). Secondly, we showed the expansion and complexity of MUP in Central Euro, occurring in tandem with the first instances of ceramic technology in the archaeological record (Murphree & Aldeias, 2022). We also found a striking pattern during the LGM, where the evidence of well described combustion features is missing in the published literature. To this end, we suggested three possible explanations: 1) publication bias, 2) preservation bias, and/or 3) lack of fire use during extreme cold periods.

In Chapter 4, I shared a case study on the combustion features found during the LGM occupations at Korman'9, Ukraine. In this study we provided a high resolution multiscale descriptive analysis of the three-combustion feature, two of which were from the same archaeological layer. Our analysis identified that two of the features were heavily cryoturbated but relatively intact. The results suggested two separate scenarios for the formation of these structures based on variations we identified in the structures and surrounding sediments. The first scenario suggest there were two separate occupations separated by an indeterminate time frame, or , the alternative scenario proposes the two structures were from the same occupation but that variation between the structures was due to site organization and/or local environmental conditions.

In Chapter 5, I presented an experimental protocol focused on observing the effects of repetitive freeze-thaw on the preservation of combustion residues and the visual recognition of combustion features in cold effected sediments. In this controlled experiment, we simulated the effects of freeze-thaw from 0, 1, 10, 30, to 60 cycles, while varying the moisture content, position of the combustion residues (buried or on the surface) and the amount of time frozen. Our results showed that freeze-thaw, as an isolated process, has very little effect on the preservation or recognition of combustion materials in controlled settings. Based on these results, we concluded that combustion

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features are generally very hard to erase completely from the archaeological record and highlighted the need to better assess the context of combustion remains in cold affected assemblages.

Finally, in Chapter 6, I reassessed the current perspectives on Upper Palaeolithic fire use based on the evidence presented in the previous Chapters. I highlighted the need to study the so called “invisible record” of non-fire use to interpret pyrotechnology and the importance of fire in human evolutionary studies. I also provide a new perspective and more fluid framework for studying fire use in the Palaeolithic of Europe.

In conclusion, this thesis provided new perspectives and evidence for a period generally overlooked in the current research paradigm. The record for pyrotechnology in the Upper Palaeolithic provides an intriguing new insight into how modern human were able to expand and adapt to an ever changing and challenging European landscape during the late Pleistocene. It also highlights a need for broader perspectives in interpreting the remains of past human behaviour – in this case, pyrotechnology.

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України.

Supplementary Information 1 : Chapter 3

Authors: William Chase Murphree¹, Vera Aldeias¹

Affiliation: ¹Interdisciplinary Center for Archaeology and the Evolution of Human Behavior (ICArEHB), University of Algarve, Faro, Portugal

Corresponding author: Vera Aldeias: vlaldeias@ualg.pt

ORCID: William Chase Murphree <https://orcid.org/0000-0003-0781-2039>, Vera Aldeias: <https://orcid.org/0000-0002-7680-182X>

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Table 8: Upper Palaeolithic sites reviewed in Chapter 3

	Site Name	Country	Lat	Long	Cave (C)/ Open Air/ Rockshelter	Fire Present	Categories (1-3)	Available Feature Data	Reference
1	Langmannersdorf	Austria	48.2943	15.8795	O	EpiAur	1	N	(Salcher-Jedrasiak et al., 2010; Verpoorte, 2004)
2	Saladorf/ Perschling	Austria	48.2763 7	15.8677 1	O	Gra	1	N	(Simon & Einwögerer, 2008)
3	Ollersdorf	Austria	48.4104 9	16.7893 3	O	Gra	1	N	(Antl-Weiser, 2008)
4	Alberndorf	Austria	48.7020 5	16.0916 2	O	Late Au	1	N	(Steguweit & Trnka, 2008)
5	Berdyzh	Belarus	52.8419 5	30.9567 8	O	Gra	1	N	(Klein, 1974; Soffer, 1985)
6	Siuren I	Crimea	44.6384	33.8506	R	Au	1	N	(Demidenko & Otte, 2000; Demidenko et al., 2012)
7	Stránská skála	Czechia	49.1906 6	16.6757 3	O	Au	1	N	(Svoboda, 2006; Svoboda & Bar-

									Yosef, 2003; Tostevin, 2003; Valoch, 2013)
8	Líšeň I/ Líšeň - Čtvrť	Czechia	49.2055	16.6969	O	Au	1	N	(Demidenko et al., 2017; Škrdla, 2017a; Škrdla et al., 2016)
9	Vedrovice V	Czechia	49.0183	16.3651	O	Au	1	N	(Demidenko et al., 2017; Oliva, 1989a; Škrdla, 2017a; Škrdla et al., 2016)
10	Líšeň VIII / Líšeň - Nad výhonem	Czechia	49.2055	16.6969	O	Au	1	N	(Škrdla, 2017a; Škrdla et al., 2016)
11	Podoli V	Czechia	49.2055	16.6969	O	Au	1	N	(Demidenko et al., 2017; Škrdla, 2017a; Škrdla et al., 2016)
12	Napajedla III	Czechia	49.1755 2	17.4995	O	Au	1	N	(Demidenko et al., 2017; Škrdla, 2017a)
13	Mladec cave	Czechia	49.7065 1	17.0156 8	C	Au	1	N	(Svoboda, 2001; Teschler-Nicola, 2007)
14	Orřechov IV	Czechia	49.1258 1	16.5132 5	O	Boh	1	N	(Škrdla, 2017a; Škrdla et al., 2016)
15	Předměstí	Czechia	49.4600 8	17.4560 7	O	Gra	1	N	(Beresford-Jones et al., 2010;

									Svoboda et al., 2013)
16	Milovice I	Czechia	48.8433 7	16.6894 6	O	Gra	1	N	(Brugère et al., 2009; Oliva, 1989b; Svoboda et al., 2005)
17	Kulna Cave	Czechia	49.6666 7	17.2166 7	C	Mag	1	N	(Neruda, 2017)
18	Balcarka Cave	Czechia	49.6166 7	17.25	C	Mag	1	N	(Moník et al., 2019)
19	Moravsky Krumlov IV	Czechia	49.0452	16.411	O	MP, Sze	1	N	(Neruda & Nerudová, 2010)
20	Pod Hradem	Czechia	49.3717 3	16.7226 6	C	MP, Sze, Au	1	N	(Nejman et al., 2018; Nejman et al., 2017)
21	Isturitz	France	43.3667	-1.1961	C	Au	1	N	(Barshay-Szmidt et al., 2018b; Szmidt et al., 2010; Villa et al., 2002)
22	La Quina-Aval	France	45.4980 7	0.28764	RS	Au	1	N	(Verna et al., 2012)
23	Grotte XVI	France	44.8101 4	1.15898	C	Au	1	N	(Karkanas et al., 2002)
24	Le Piage	France	44.8044 4	1.38972 2	C	Au	1	N	(Bordes et al., 2006; Costamagno et al., 2009; Villa et al., 2002)
25	Brassempouy	France	43.6380	-0.692	C	Au	1	N	(Henry-Gambier

	Grotte des Hyenes		6						et al., 2004; Villa et al., 2002)
26	Caminade-est	France	44.879	1.257	C	Au	1	N	(Bordes, 2000; Laville & de Sonneville-Bordes, 1967; Villa et al., 2002)
27	Brassempouy Grotte du Papes	France	43.6380 6	-0.692	C	Au	1	N	(Henry-Gambier et al., 2004)
28	Abri Blanchard	France	44.9991 3	1.10204 2	C	Au	1	N	(White et al., 2017)
29	le Trou de la Chèvre à Bourdeilles	France	43.321	0.581	C	Au	1	N	(Villa et al., 2002)
30	Grotte Tournal	France	43.3167	2.8833	C	Au	1	N	(Villa et al., 2002)
31	Flageolet I	France	44.85	1.0833	C	Au, Gra	1	N	(Rigaud, 2016; Simek, 1984; Villa et al., 2002)
32	Chauvet Cave	France	44.387	4.424	C	Au, Gra	1	N	(Salmon et al., 2020; Théry-Parisot et al., 2018)
33	Abri du Facteur	France	44.9588 3	1.03121	C	Au, Gra	1	N	(White et al., 2017)
34	La Tuto De Camalhot	France	43.0104	1.6285	C	Au, Gra	1	N	(Bon, 2002)
35	Quincay	France	46.6074 2	0.23585	C	Chat	1	N	(Lévêque, 1979; Lévêque, 1997; Lévêque & Miskovsky, 1983; Roussel &

									Soressi, 2010a)
36	Abri de la Souquette	France	45.0006 1	1.09945 6	C	EUP	1	N	(White et al., 2017)
37	Roc de Combe	France	44.7669 4	1.34583 3	C	Gra	1	N	(Grayson & Delpech, 2008; Zilhão & d'Errico, 1999)
38	Arcy sur Cure, Grotte du Rennes	France	47.5911 2	3.76499	C	Gra	1	N	(Villa et al., 2002)
39	La Vigne Brun	France	45.9822	4.0286	O	Gra	1	N	(Digan, 2008)
40	La Picardie	France	46.8397 2	0.93626 9	C	Gra	1	N	(Delvigne et al., 2020; Klaric et al., 2018)
41	Laugerie-Haute	France	44.9523 4	1.00146	C	Gra-Sol	1	N	(Schmidt & Morala, 2018; Verpoorte et al., 2019)
42	Roc-aux-Sorciers	France	46.7045 2	0.87917	RS	Mag	1	N	(Bourdier, 2013)
43	Combe Sauniere IV	France	45.2307	0.8836	C	Sol	1	N	(Villa et al., 2004)
44	Le Cuzoul de Vers	France	44.45	1.5333	RS	Sol	1	N	(Ducasse et al., 2014; Villa et al., 2002)
45	Chauvet-Pont d'Arc	France			Cave	Au	1	N	(Salmon et al., 2020)
46	Bockstein	Germany	48.5541 4	10.1547 5	C	Au	1	N	(Bolus, 2015)
47	Vogelherd	Germany	48.5588 6	10.1945 3	C	Au	1	N	(Niven, 2007)
48	Hohlenstein- Stadel	Germany	48.5541	10.1547	C	Au	1	N	(Bolus, 2015)

			4	5					
49	Sirgenstein	Germany	48.3853	9.7617	C	Au	1	N	(Bolus, 2015)
50	Breitenbach-Schneidemühle	Germany	51.00869	12.08522	O	Au	1	N	(Moreau, 2012)
51	Lommersum	Germany	50.7	6.804	O	Au	1	N	(Bosinski et al., 1995)
52	Friedrichsdorf-Seulberg	Germany	50.24761	8.651596	O	Au	1	N	(Moreau & Terberger, 2019)
53	Wiesbaden-Igstadt	Germany	50.08333	8.316667	O	Au	1	N	(Street & Terberger, 1999)
54	Remagen-Schwalbenberg	Germany	50.55718	7.23293	O	EUP	1	N	(Bosinski et al., 1995)
55	Koblenz-Metternich	Germany			O	Gra	1	N	(Bosinski et al., 1995)
56	Sprendlingen	Germany	49.85872	7.994447	O	Gra	1	N	(Bosinski et al., 1995)
57	Mainz-Linsenberg	Germany	49.97029	8.252569	O	Gra	1	N	(Bosinski et al., 1995)
58	Brillenhohle	Germany	48.40516	9.777569	C	Gra, Mag	1	N	(Conard & Bolus, 2003)
59	Munzingen	Germany	47.9707	7.70083	O	Mag	1	N	(Bosinski et al., 1995)
60	Oelknitz 3	Germany	50.835	11.66667	O	Mag	1	N	(Gaudzinski-Windheuser, 2012, 2015)
61	Gönnersdorf	Germany	50.44778	7.415278	O	Mag	1	N	(Street et al., 2012)
62	Andernach-Martinsberg	Germany	50.43337	7.40005	O	Mag	1	N	(Bosinski et al., 1995; Street et al., 2012)

63	Alsdorf	Germany			O	Mag	1	N	(Bosinski et al., 1995)
64	Istállóskő Cave	Hungary	48.0716 2	20.4176 5	C	Au	1	N	(Patou-Mathis et al., 2016)
65	Szeleta Cave	Hungary	48.1085 8	20.6652 1	C	Sze, Au	1	N	(Lengyel et al., 2016)
66	Riparo Mochi	Italy	43.7841	7.5348	C	ProtoAu	1	N	(Frouin et al., 2022; Holt et al., 2019)
67	Cosautsi	Moldova	48.2166 7	28.2833 3	O	EpiGra	1	N	(Haesaerts et al., 2003)
68	Deszczowa Cave	Poland	50.5833	19.5166 7	C	Au	1	N	(Wojtal, 2007)
69	Dziadowa Skala	Poland			C	Gra	1	N	(Wojtal, 2007)
70	Jaksice II	Poland	50.1436 2	20.5037 3	O	Gra	1	N	(Wilczyński et al., 2015a)
71	Klementowice	Poland	51.3408 3	22.1491 7	O	Mag	1	N	(Wiśniewski et al., 2012; Wojtal, 2007)
72	Nietoperzowa Cave	Poland	50.1943 4	19.7457	C	MUP	1	N	(Krajcarz et al., 2018; Wojtal, 2007)
73	Lapa do Anecrial	Portugal	39.32	-8.45	C	Gra	1	N	(Brugal, 2006)
74	Cardina 1	Portugal	40.9791	-7.0995	C	Gra	1	N	(Bergadà, 2009)
75	Foz do Medal	Portugal	41.1499	-6.8065	O	Gra	1	N	(Gaspar et al., 2016)
76	Olga Grande	Portugal	40.9694	-7.0564	C	Gra	1	N	(Aubry, 1998; Aubry & Sampaio, 2003a, 2003b; Sellami,

									2009)
77	Romanesti-Dumbravita I	Romania	45.8173 1	22.3208 6	O	Au	1	N	(Schmidt et al., 2013)
78	Mitoc Malu Galben	Romania	48.0977 4	27.0230 4	O	Au, Gra	1	N	(Nigst et al., 2021; Noiret & Otte, 2010)
79	Tibrinu	Romania	44.3192	28.0708 1	O	EpiGra	1	N	(Anghelinu et al., 2018; Marin et al., 2010)
80	Kostenki 1	Russia	51.3953	39.0415	O	Au?	1	N	(Hoffecker et al., 2016; Holliday et al., 2007)
81	Sungir	Russia	56.175	40.5083 3	O	EUP	1	N	(Soldatova, 2019)
82	Kostenki 12	Russia	51.3946 8	39.0479 5	O	EUP	1	N	(Anikovich et al., 2007)
83	Borschevo 5	Russia	51.3958 6	39.0412 6	O	Gra	1	N	(Lisitsyn, 2015)
84	Kostenki 13	Russia	51.3958 6	39.0412 6	O	Gra	1	N	(Sinitsyn & Sanz, 2015)
85	Kostenki 11	Russia	51.3855 3	39.052	O	Gra	1	N	(Pryor et al., 2020a; Sinitsyn & Sanz, 2015)
86	Kostenki 4	Russia	51.3768 1	39.0703 2	O	Gra	1	N	(Sinitsyn & Sanz, 2015; Zheltova, 2015)
87	Kostenki 8	Russia	51.3727 7	39.0672 9	O	IUP	1	N	(Sinitsyn & Sanz, 2015)
88	Trabula Traiana Cave	Serbia	44.6530 9	22.3060 4	C	EUP	1	N	(Borić et al., 2012)

89	Bukovac Cave	Serbia	45.3680 2	14.7586 6	C	Gra	1	N	(Dogandžić et al., 2014)
90	Velika Pecina	Serbia	44.0364	15.5586 1	C	Gra	1	N	(Kuhn et al., 2014; Stiner et al., 2022)
91	Tibava	Slovakia				Au	1	N	(Svoboda & Simán, 1989)
92	Barca II	Slovakia	48.6435	21.3254	O	Au	1	N	(Svoboda & Simán, 1989)
93	Moravany-Lopata	Slovakia	48.6060 9	17.8836 7	O	Gra	1	N	(Pawlikowski et al., 1998)
94	Trencianske Bohuslavice	Slovakia	48.7998 9	17.8525 1	O	Gra	1	N	(Kaminská, 2016; Vlačíky et al., 2013)
95	Potočka Zijalka	Slovenia	46.4492 9	14.6691 3	C	Au	1	N	(Verpoorte, 2012)
96	Cova Foradada	Spain	41.2046 7	1.58099	C	Au	1	N	(Morales et al., 2019)
97	Cueva Morin	Spain	43.3769	-3.858	C	Au, Gra	1	N	(Bradtmöller, 2015; Bradtmöller et al., 2016)
98	El Castillo	Spain	43.2924	-3.9656	C	Au, Gra	1	N	(Bernaldo de Quirós et al., 2015; Wood et al., 2018)
99	Finca Dona Martina	Spain	38.0786 7	-1.49031	R	Gra	1	N	(Angelucci et al., 2018)
100	Coimbre Cave	Spain	43.3266 7	-4.68722	C	Gra	1	N	(López-Cisneros et al., 2019;

									Yravedra et al., 2016)
101	Cueva Ambrosio	Spain	37.83429	-2.09203	C	Sol	1	N	(López et al., 2015)
102	Pena Capon	Spain	40.95833	-3.20222	C	Sol	1	N	(Alcaraz-Castaño et al., 2019)
103	Dobranichevka	Ukraine	50.0333	32.6667	O	EpiGra	1	N	(Klein, 1974)
104	Mira	Ukraine	47.66667	34.83333	O	EUP	1	N	(Stepanchuk, 2005)
105	Doroshivtsi III	Ukraine	48.59378	25.86964	O	Gra	1	N	(Kulakovska et al., 2015)
106	Mezin	Ukraine	51.7335	33.0833	O	Late Gra	1	N	(Klein, 1974)
107	Puchkari I	Ukraine	52.1400	32.2333	O	Late Gra	1	N	(Klein, 1974)
108	Lipa I	Ukraine	50.43858	25.12855	O	Late Gra	1	N	(Klein, 1974)
109	Beregovo	Ukraine	48.19505	22.61275	O	ProtoAu	1	N	(Usik et al., 2014)
110	Galenburg-Stratzing	Austria	48.4303	15.606	O	Au	2	N	(Brandl et al., 2015; Neugebauer-Maresch, 2008b; Thiel et al., 2011)
111	Krems-Wachtburg	Austria	48.41493	15.5996	O	Gra	2	Y	(Cichocki et al., 2014; Fladerer et al., 2014; Händel et al., 2014; Händel et al., 2015; Händel et al., 2009; Lomax et al., 2014;

									Simon et al., 2014; Terhorst et al., 2014; Thomas & Ziehaus, 2014)
112	Krems-Hundssteig	Austria	48.41458	15.60214	O	Gra	2	N	(Neugebauer-Maresch, 2003; Neugebauer-Maresch, 2008a; Neugebauer-Maresch, 2008c; Wild et al., 2008; Wild et al., 2016)
113	Grub/Kranawetburg	Austria	48.42363	16.82726	O	Gra	2	Y	(Antl-Weiser, 2008; Bosch et al., 2012; Nigst & Antl-Weiser, 2012; Schilt et al., 2017; Teschler-Nicola et al., 2004; Zöller et al., 2013)
114	Grubgraben	Austria	48.4779	15.7022	O	EpiGra	2	Y	(Einwögerer, 2021; Haesaerts et al., 2016; Händel et al., 2021; Montet-White & Williams, 1994; Neugebauer-Maresch et al., 2016)

115	Bacho Kiro	Bulgaria	42.9333	25.4167	C	IUP	2	N	(Fewlass et al., 2020; Hublin et al., 2020; Kozłowski, 1982)
116	Dolní Věstonice I (DV)	Czechia	48.88036	16.6692	O	Gra	2	Y	(Pryor et al., 2016; Sázelová & Hromadová, 2020; Svoboda et al., 2018; Svoboda, 2015; Vandiver et al., 1989; Verpoorte, 2000; Wilczyński et al., 2015b)
117	Pavlov I	Czechia	48.87735	16.6749	O	Gra	2	Y	(Adovasio et al., 1996; Fewlass et al., 2019; Pryor et al., 2016; Svoboda, 2005; Svoboda et al., 1997; Svoboda et al., 2016; Svoboda, 2015; Verpoorte, 2000; Wojtal et al., 2012)
118	Pavlov IV	Czechia	48.86979	16.68414	O	Gra	2	N	(Svoboda et al., 2009; Svoboda, 2015)
119	Dolní Věstonice II (A and 05)	Czechia	48.88436	16.65386	O	Gra	2	Y	(Fewlass et al., 2019; Pryor et al.,

									2016; Škrdla, 2017b; Svoboda et al., 2015; Svoboda, 2015; Svoboda, 2016)
120	Milovice IV	Czechia	48.85226	16.69848	O	Gra	2	N	(Brugère et al., 2009; Svoboda et al., 2011; Svoboda, 2015)
121	La Ferrassie	France	44.95343	0.941572	C	Au	2	N	(Frouin et al., 2017; Guérin et al., 2015; Talamo et al., 2020)
122	Chez-Pinaud 2	France	45.4377	-0.4193	O	Au	2	Y	(Airvaux et al., 2003; Airvaux & Soressi, 2005)
123	Abri Castanet	France	44.99913	1.102042	C	Au	2	Y	(White et al., 2012; White et al., 2017)
124	Abri Cellier	France	44.96499	1.02308	C	Au	2	Y	(White et al., 2017)
125	Abri Pataud	France	44.9369	1.012802	C	Au, Gra/Per	2	Y	(Beck et al., 2011; Braadbaart et al., 2020; Chiotti et al., 2015; Higham et al., 2011; Marquer et al., 2010; Movius et al., 1977; Movius Jr, 1966; Théry-Parisot, 2002)

126	Les Bossats	France	48.2512 2	2.66144	O	Gra	2	Y	(Bodu et al., 2014; Lacarrière et al., 2015; Lejay, 2018)
127	Auneau	France	48.4765 3	1.75470 4	O	Gra	2	N	(Soressi et al., 2013)
128	Ságvár Lyukas Hill	Hungary	46.8333	18.1137	O	Gra	2	N	(Bösken et al., 2018; Lengyel, 2010)
129	Santa Maria d'Agnano	Italy	40.7481 8	17.5478	C	EpiGra	2	N	(Chakroun et al., 2020)
130	Rio Secco	Italy	46.2809	12.9714	C	Gra	2	N	(Peresani et al., 2014; Talamo et al., 2014)
131	Henrykow 15	Poland	50.6436 2	16.9969 7	O	Gra	2	N	(Wiśniewski et al., 2015)
132	Krakow Spadzista	Poland	50.0628 7	19.8932 3	O	Gra	2	N	(Wilczyński et al., 2012; Wilczyński et al., 2015c; Wojtal, 2007)
133	Lagar Velho	Portugal	39.7569 4	-8.73278	R	Gra	2	N	(Almeida et al., 2009)
134	Vale Boi	Portugal	37.0944	-8.815	O	Gra	2	N	(Belmiro et al., 2020; Bicho et al., 2003; Bicho et al., 2013; Manne, 2014)
135	Lapa do Picareiro	Portugal	39.5305	-8.652	C	Sol, Mag	2	N	(Belmiro et al., 2020; Benedetti et al., 2019; Bicho

									et al., 2019; Bicho et al., 2006; Haws et al., 2020)
136	Bistricioara-Lut ^{ar} arie III	Romania			O	Gra, EpiGra	2	Y	
137	Kostenki 14	Russia	51.39026	39.03473	O	EUP, Au	2	Y	(Anikovich et al., 2007; Douka et al., 2017; Hoffecker & Anikovich, 2014; Holliday et al., 2007; Sedov et al., 2010; Sinitsyn & Sanz, 2015; Sinitsyn, 2004; Sinitsyn & Hoffecker, 2006)
138	Cejkov I	Slovakia	48.46505	21.7699	O	Gra	2	Y	(Kaminská, 2016; Kaminská & Tomášková, 2004)
139	Abrigo de La Boja	Spain	38.07861	-1.48972	R	Gra, Sol	2	N	(Angelucci et al., 2018; Badal et al., 2019; Lucena et al., 2013; Zilhao et al., 2017)
140	Cendres Cave	Spain	38.6859	0.1522	C	Mag	2	N	(Bergadà et al., 2013; Martínez-Varea et al., 2020; Villaverde Bonilla, 1985;

									Villaverde et al., 2019)
141	El Parco	Spain	41.9086 1	0.94194	C	Mag	2	N	(Allué et al., 2013; Fullola et al., 2012)
142	Bauma de la Peixera d'Alfès	Spain	41.5256 5	0.6278	C	Mag	2	N	(Fullola et al., 2012)
143	Els Colls	Spain	41.4760	1.4240	R	Mag	2	N	(Fullola et al., 2012)
144	Can Garriga 1	Spain	42.0294	2.83157	O	Mag	2	N	(Fullola et al., 2012)
145	Moli de Salt	Spain	41.4015	1.05341	R	Mag	2	N	(Fullola et al., 2012; Gaspar et al., 2015; Rufà et al., 2017; Vaquero et al., 2012)
146	Montlleó	Spain	42.3819 9	1.84821	C	Mag	2	N	(Fullola et al., 2012; Fullola et al., 2019)
147	L'Hort de la Boquera	Spain	41.2994	0.7583	C	Mag	2	N	(Fullola et al., 2012; García-Argüelles Andreu et al., 2014; Garcia-Argüelles Andreu et al., 2015)
148	Cova Gran de Santa Linya	Spain	41.9272	0.8128	C	MP, EUP, Gra	2	N	(Martinez-Moreno et al., 2010; Sánchez-

									Martínez et al., 2020)
149	Ratlla del Bubo	Spain	38.25	-0.8	C	Sol-Gra	2	N	(Badal et al., 1990; Menarques & Poveda, 2001)
150	Cova de les Malladetes	Spain			C	Au, Gra	2	Y	(Villaverde et al., 2021)
151	Korman 9	Ukraine	48.5737 7	27.1483 6	O	EpiGra	2	N	(Kulakovska et al., 2021; Кулаковська et al., 2019)
152	Mezhyrich	Ukraine	49.6340 8	31.4349 5	O	EpiGra	2	N	(Klein, 1974; Marquer et al., 2015; Marquer et al., 2012; Soffer et al., 1997)
153	Régismont-le-Haut	France	43.3057 4	3.10042 7	O	Au	3	Y	(Anderson & Lejay, 2018; Anderson et al., 2018; Barshay-Szmidt et al., 2018a; Bon et al., 2007; Lejay, 2018)
154	Verberie	France	49.3062 7	2.73077	O	Mag	3	Y	(Audouze & Enloe, 1997; Enloe, 1997; Wattez, 1994)
156	Pincevent	France	48.3872 3	2.90656	O	Mag	3	Y	(Enloe, 2000; Julien et al.,

									1987; Leroi-Gourhan & Brézillon, 1966; Simek, 1984; Wattez, 1994)
157	Etiolles	France	48.63819	2.45981	O	Mag	3	Y	(Caron-Laviolette et al., 2018; Wattez, 1994)
158	Hohle Fels	Germany	48.37906	9.753869	C	Au, Gra	3	Y	(Barth, 2004; Dinnis et al., 2019; Goldberg et al., 2017; Goldberg et al., 2003; Miller, 2015; Miller et al., 2010; Schiegl et al., 2003a)
159	Geißenklösterle	Germany	48.39806	9.7714	C	Au, Gra	3	Y	(Conard et al., 2003; Higham et al., 2012b; Miller, 2015; Moreau, 2010; Richter et al., 2000)
160	Klisoura I	Greece	37.6897	22.8076	C	Au	3	Y	(Karkanas et al., 2004; Koumouzelis et al., 2001)
161	Theopetra Cave	Greece	39.66667	21.67944	C	EUP	3	N	(Karkanas, 2001; Karkanas et al., 2015)
162	Grotte de Fumane	Italy	45.5062	10.9666	C	Au	3	N	(Falcucci et al.,

									2016; López-García et al., 2015; Marcazzan et al., 2022)
163	El Miron Cave	Spain	43.2435	-3.4516	C	Mag	3	Y	(Arroyo, 2009; González Morales & Straus, 2015; Nakazawa et al., 2009; Straus & González Morales, 2019; Straus et al., 2013)
164	Cueva de Nerja	Spain	36.76228	-3.8451	C	Sol	3	N	(Medina-Alcaide et al., 2019; Medina-Alcaide et al., 2021; Medina-Alcaide et al., 2015)

Abbreviations: C- Cave, O- Open air, RS – Rock Shelter, MP- Middle Paleolithic, IUP- Initial Upper Paleolithic, 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- Solutrean-Gravettian, Mag – Magdalenian, EpiGra- EpiGravettian

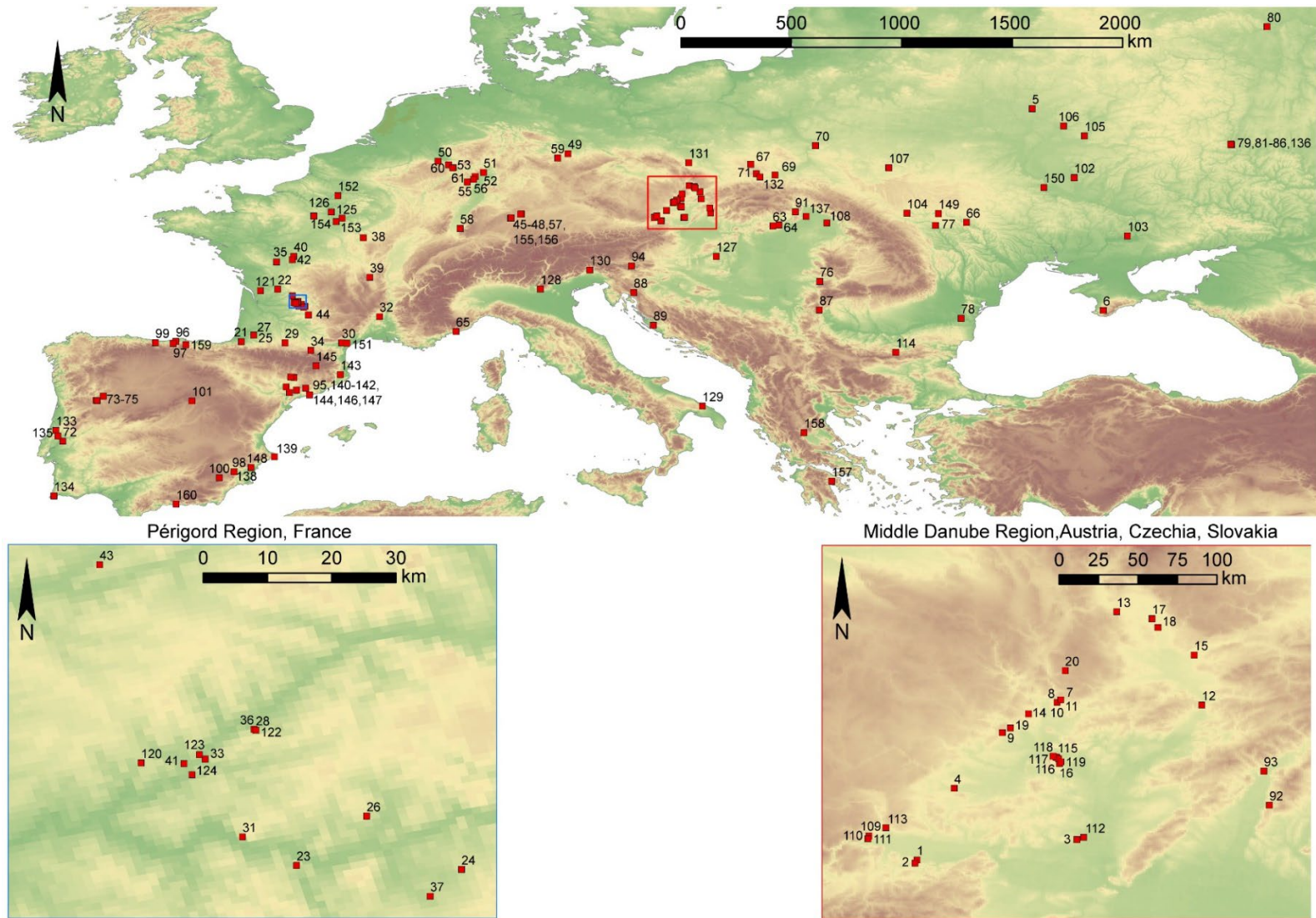


Figure 38: Map of Reviewed sites outlined in Table 9

Additional individual feature data available online:

<https://link.springer.com/article/10.1007/s12520-022-01660-w#Sec8>

Supplementary Information 2: Chapter 4

Authors: William Chase Murphree^{1,*}, Cruz Ferro-Vázquez², Larissa Kulakovska³, Vitaly I. Usyk^{3,4}, Olesia Kononenko³, Marjolein D. Bosch^{5,6,7}, Paul Haesaerts⁸, Freddy Damblon⁸, Stéphane Pirson^{9,10}, Philip R. Nigst^{11,7,**}, Vera Aldeias^{1,**2}

Affiliations:

1) Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), University of Algarve (Portugal)

2) INCIPIT-CSIC, Cidade da Cultura, Edificio Fontán, Santiago de Compostela, Spain

3) Institute of Archaeology, National Academy of Sciences of Ukraine, Kyiv, Ukraine

4) Institute of Archaeology, Czech Academy of Sciences, Brno, Czechia

5) Research Group Prehistoric Identities, Department of Prehistory and Western Asia and North African Archaeology, Austrian Archaeological Institute, Austrian Academy of Sciences, Vienna, Austria

6) Turkana Basin Institute, Turkana, Kenya, & Turkana Basin Institute, Stony Brook University, New York, US

7) Human Evolution and Archaeological Sciences (HEAS), University of Vienna, Vienna, Austria

8) Royal Belgian Institute of Natural Science, Brussels, Belgium

² * Corresponding Author: William Chase Murphree, Email: wmurphree@ualg.pt

** Co-Last Authors: Philip R. Nigst and Vera Aldeias

9) Agence wallonne du Patrimoine (AWaP), Service Public de Wallonie, Direction d'appui scientifique et technique, Jambes, Belgium

10) European Archaeometry Centre and Department of Geology, University of Liège, Belgium

11) Department of Prehistoric and Historical Archaeology, University of Vienna, Vienna, Austria

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1.0 Photogrammetry models

Photogrammetry models were produced using the Agisoft Metashape professional program. Photos were taken using a NIKON D7000 DSLR camera during the 2013 field season by P.R.Nigst . The initial goal of the photography was to take high resolution section photographs representative of stratigraphy of the site and highlight features during the 2013 field season. Here we repurposed the photographs to build scaled 3-D models to better understand the context around the three combustion features at Korman'9, as well as to make a morphological analysis and measurements. This was done in conjunction with the micromorphological analysis to provide a high-resolution description of the combustion features at the site. Figures 39-46 are finished models of CF1 (Phase 0 – Figures 39 and 40, Phase 3- Figures 41 and 42), CF2 (Figures: 43 & 44), and CF3 (Figures: 45 and 46)

1.1 Agisoft Settings

Each model was built using several photographs (Table 9). Once inputted into the system, the program finds and aligns the photographs based on the camera's position and settings. This results in a sparse point cloud and camera positions. Next, we created a dense cloud based on the estimate camera position and images themselves. The program uses overlapping image pairs to create a depth map based on their orientation with the noise filtering for overlapping images. The dense cloud for 3D model was created using medium quality and mild filtering. The textures are diffused map type sourced from the images. The quality is based on the amount of detail and accurate geometry. In this case, we selected medium to save on processing time and due computer constraints. The mild filtering removes most outliers from while preserving important features. Higher filtering

settings are usually reserved for the processing aerial photographs where small details are not needed. These models were georeferenced using excavation grid, ground control points added during the excavation and/or scales within the photographs.

Table 9: number of photos used to create each of the 3D models

3D MODEL	NUMBER OF PHOTOS
CF1- PHASE 0	12
CF1- PHASE 3	40
CF2	48
CF3	15



Figure 39: CF1 Phase 0 Model produced in Agisoft Metashape.



Figure 40: CF1 Phase 0 model with scale bars. Scale bars were based on the georeferenced grid and ground control points created during the excavation.



Figure 41: CF1 Phase 3 model produced in Agisoft Metashape



Figure 42: CF1 Phase 3 model with scale bars. Scale bars based on georeferenced ground control points, grid and scales within the photograph.



Figure 43: CF2 model produced in Agisoft Metashape

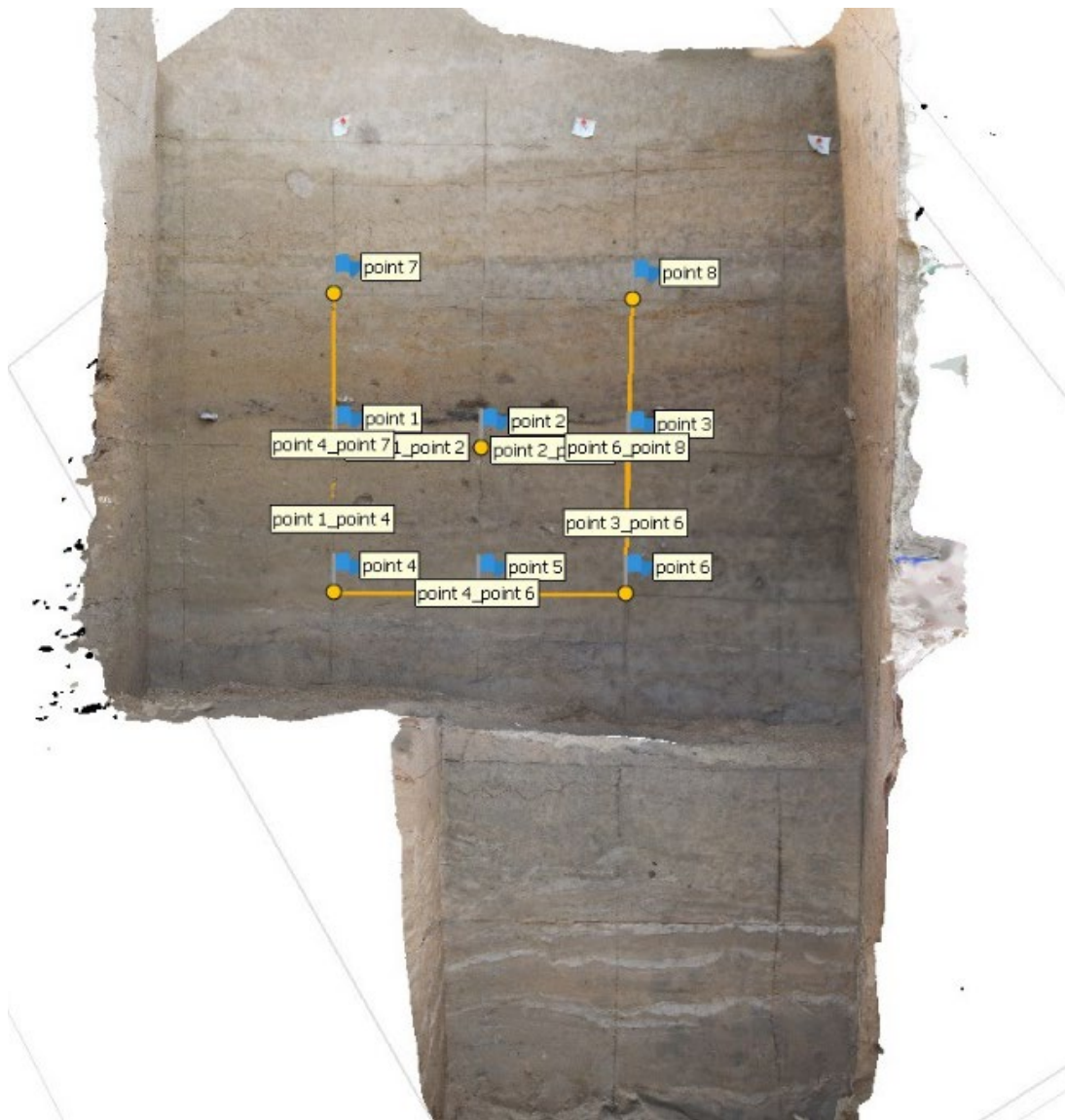


Figure 44: CF2 model with scale bars. Scale bars based on georeferenced grid and ground control points

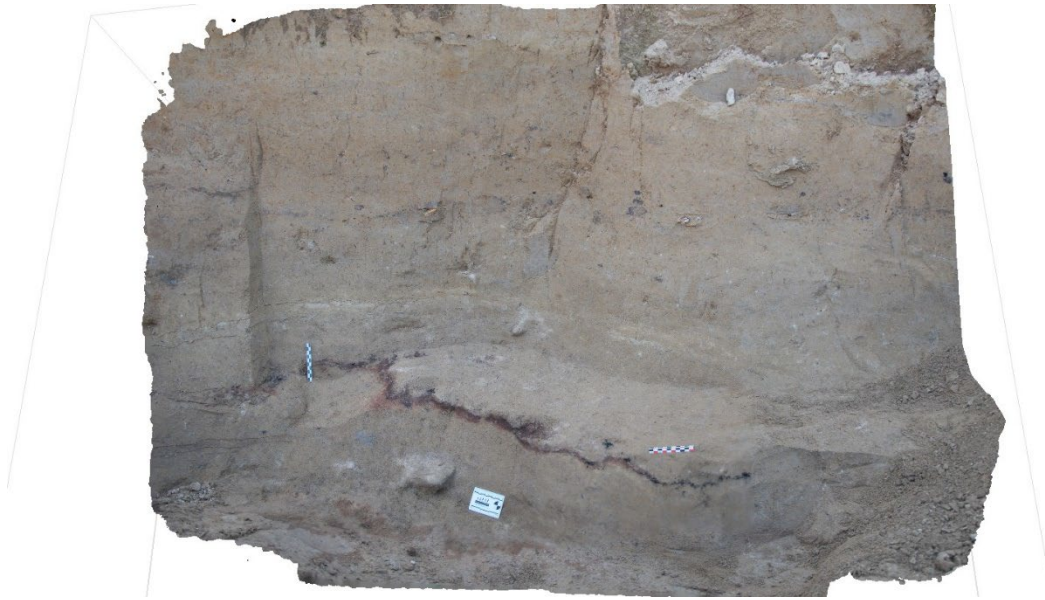


Figure 45: CF3 model produced in Agisoft Metashape

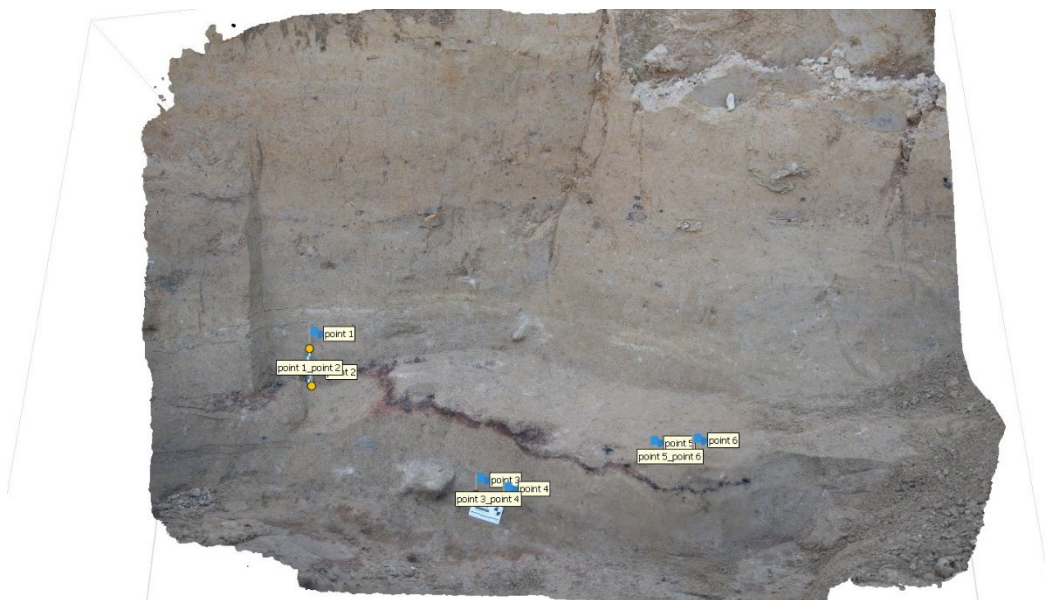


Figure 46: CF3 model with scale bars. Scale bars based on scales rendered into the model

2.0 Assessing heating using photographs

In order to test if picture colours can provide information on the thermal history of the depicted sediments, we first addressed an assessment of the colours of pictures taken to samples that had been heated and their colour characterized in the laboratory in a previous study (methodological details are provided in Ferro-Vázquez et al. (2021)). An

aliquot of each sample heated to 100, 200, 300, 400, 500, 600, 800 and 1000°C was placed on a white paper and levelled in order to reduce shading artefacts, as noted in Levin et al (2005).

Photographs were taken with a Canon EOS 6D Mark II and with a built-in mobile phone camera (model Xiaomi Redmi Note 7) under both natural and controlled artificial light conditions. The RGB data of regions of the pictures representative of each temperature were extracted and converted to the CIE Lab system of the Commission on Illumination (CIE). The CIE Lab system consists in three orthogonal parameters L^* , a^* and b^* . The L^* represents lightness ranging from 0 (black) to 100 (white) and corresponds to the z-axis of the three-dimensional CIE Lab space, while the a^* and b^* are the chromatic coordinates from green to red and from blue to yellow and correspond to the x and y axes. The measurements were carried out using the LOOMATIX Ltd. ColorGrab™ mobile app v3.9.2, and conversion considered a D65 illuminant for indirect daylight, D50 for direct noon daylight, and A for artificial light, at a 2° angle.

Following the protocol detailed in Ferro-Vázquez et al. (2021), we use a standardization of the colour data using an internal standard, i.e. a part of the picture that reflects a presumed unburnt area with an analogous composition, weathering degree and age to that of the area of the photo that is being interrogated. The following calculations were used:

$$\Delta L = (L^*_t - L^*_{T0})$$

$$\Delta a = (a^*_t - a^*_{T0})$$

$$\Delta b = (b^*_t - b^*_{T0})$$

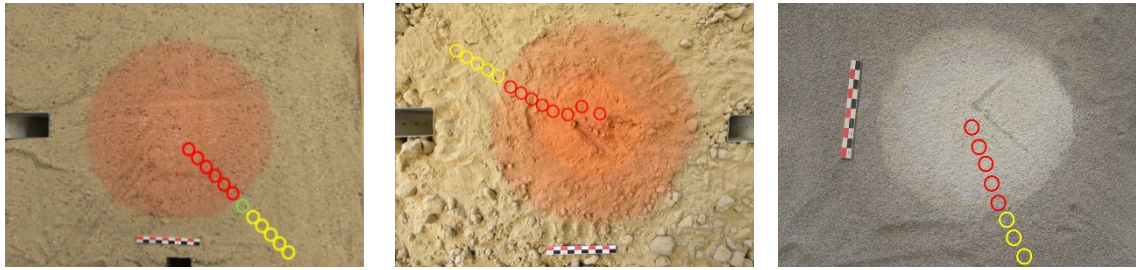
where ΔL , Δa and Δb are, respectively, the difference in lightness (L^*), red (a^*) and yellow (b^*) of the target sample (t) respecting to the chosen internal standard (unheated) sample (T0). The colour of T0 thus acts as internal standard for a reliable assessment of colour variations. This standardization is intended to eliminate the effects of the camera characteristics and settings and of the specific light and soil conditions at the moment in which the photograph was taken.

Further assessments of the suitability of pictures for reflecting thermal transformations of sediments consisted of the evaluation of pictures of experiments performed by Aldeias et al. (2016). Their experimental design consisted in heating different kinds of sediments, carefully controlling the most important variables underlying the transfer of heat to subsurface sediments, including heating temperature and duration, and composition and texture of the sediments. The colours of photographs of three of the experiments from Aldeias et al. (2016) were measured using the protocol explained above, and the temperature estimations obtained from the colours of the photographs using Ferro-Vázquez et al. (2021) equations were compared with the actual heating temperatures and durations measured by Aldeias et al. (2016).

In order to account for sample surface heterogeneity, 10 points were measured, and the values that differed from the average more than 3 times the standard deviation were excluded.

2.1 Data handling

Figure 47: Photos of the experimental setting from Aldeias et al (2016) and sampling strategy for this study. Yellow circles are T0 measurements and red circles are target measurements.



The values of ΔL , Δa and Δb of the pictures were compared through correlation analyses with the colour data obtained by Ferro-Vázquez et al. (2021) in laboratory conditions, in order to evaluate the capacity of the photographs for reflecting temperature-related colour variations.

The ΔL , Δa and Δb obtained from the pictures were strongly correlated with the data acquired in the laboratory study ($r^2=0.86$, $p<0.01$, Figure X). The slope of the correlation function between the two datasets was 1.311, meaning that the values of ΔL , Δa and Δb obtained for the photographs are 31.1% higher than values from the benchtop colorimeter. Since this is a systematic bias, ΔL , Δa and Δb were corrected applying a 0.689 factor before they are employed in the discriminant equations for heating identification and for calculating the temperature of heating.

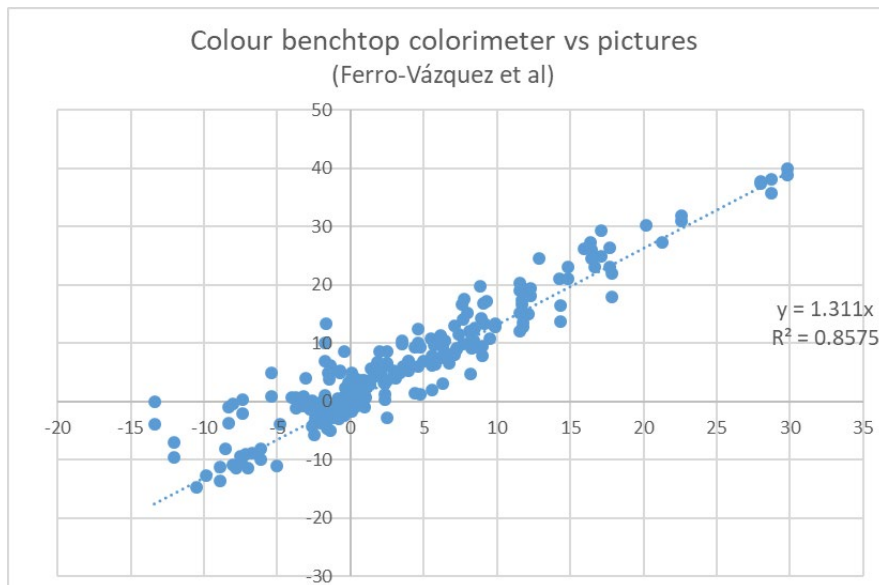


Figure 48: Correlation between the differentials (ΔL^ , Δa^* , and Δb^*) of the direct sample measurements and of the colours measured in the photographs.*

Lower correlation coefficients are found if the samples are considered individually, particularly in the more heterogeneous samples, be heterogeneity due to the sample composition or to the sample preparation for the picture (e.g. difficulties for achieving a levelled surface that avoids shades and reflections). The light conditions under which a given picture has been taken do not seem to matter as long as light is reasonably uniform within each picture, as supported by the excellent ($r^2 < 0.9$, $p < 0.01$) correlation between the values of samples photographed under different light conditions.

The heterogeneity of the materials and the lack of a flat surface imply that an unknown part of the colour variability observed in the pictures is not due to the effect of heating. The results obtained in terms of presence of heating and temperature estimations are nonetheless satisfactory, with a high accuracy in the identification of heated vs unheated sediments, and only a bit less accurate in the calculation of the temperature of heating. This method is designed to assess colour variations within a given picture and does not allow the comparison between different photographs (so using the T0 from one picture

for assessing heating in other pictures from the same site), in which lighting conditions will be different. Regarding the light conditions, usual practice involves the use of a controlled source of artificial illumination to avoid inconsistencies due to the light source (Fisher et al., 2015; Yam & Papadakis, 2004), and the posterior calibration of the pictures using different methodologies (see e.g. Fisher et al., 2015; Levin et al., 2005) for ensuring that the colour assessment is consistent and allowing intercomparisons between pictures. Levin et al. (2005) used standard colour chips with that end, but they noted that uncalibrated digital camera measurements were as effective in characterizing colour indexes as calibrated digital camera measurements. It is necessary, in any case, to ensure that the light conditions of the T0 pixels are the same than the target area, i.e. not selecting shade areas of the picture for comparing with non-shade, and to evaluate the lateral and vertical heterogeneity of soil environmental conditions: for example, not comparing wet with dry areas of the picture.

Regarding potential artefacts introduced by the photograph resolution, our experiments show that the analysis of pics with different resolution consistently deliver the same outcome in terms of heating identification (see S.I. Chapter 4 calculations), as a result of the internal standard T0 used being subjected to exactly the same transformations than the part of the picture being diagnosed.

Colour Calculations:

Sample	Color Hex	Color Name	RGB-R	RGB-G	RGB-B	HSV-H	HSV-S	HSV-V	HSL-H	HSL-S	HSL-L	Lab-a	Lab-b	Lab-L	ΔL*	Δa*	Δb*	ΔL*(0.69)	Δa*(0.69)	Δb*(0.69)	CA3	CA6
ox	#8D642E	Rusty Nail	141	100	46	34.105263	0.67375886	0.5529412	34.105274	0.5080214	0.36666667	45.60078	10.76302	36.39978	-10.913316	6.48613853	17.8823857	-8.5123867	5.05918806	13.9482608	N	N
ox	#9C7F5C	Sorrell Brown	156	127	92	32.8125	0.41025642	0.6117647	32.812492	0.2580645	0.48627454	55.09349	6.185353	23.234808	-1.4206063	1.90847153	4.71741367	-1.1080729	1.4886078	3.67958266	N	N
5	#8A644F	Spicy Mix	138	100	79	21.355932	0.42753622	0.5411765	21.355919	0.27188942	0.4254902	45.747925	12.488812	17.94207	-10.766171	8.21193053	-0.5753243	-8.3976136	6.40530582	-0.448753	300	400
4	#996C50	Dark Tan	153	108	80	23.013699	0.47712418	0.6	23.013697	0.31330472	0.45686275	49.590622	14.420986	22.77229	-6.9234743	10.1441045	4.25489567	-5.40031	7.91240154	3.31881862	600	400
3	#A3775D	Toast	163	119	93	22.285715	0.42944786	0.6392157	22.285702	0.27559057	0.5019608	53.78428	13.814926	21.061356	-2.7298163	9.53804453	2.54396167	-2.1292567	7.43967474	1.9842901	400	400
2	#9B7C62	Sorrell Brown	155	124	98	27.36842	0.36774194	0.60784316	27.368402	0.22529645	0.49607843	54.309	8.20753	18.75496	-2.2050963	3.93064853	0.23756567	-1.7199751	3.06590586	0.18530122	200	400
1	#9F8A6F	Pale Oyster	159	138	111	33.75	0.3018868	0.62352943	33.75	0.20000003	0.5294118	58.692375	3.6877096	17.400265	2.17827867	-0.5891719	-1.1171293	1.69905736	-0.4595541	-0.8713609	N	N
T0	#967F64	Sorrell Brown	150	127	100	32.4	0.33333334	0.5882353	32.39997	0.2	0.4901961	54.641014	4.6685038	17.976677	0	0	0	0	0	0	N	N
T0	#9F896D	Sandal	159	137	109	33.6	0.3144654	0.62352943	33.59999	0.2066116	0.5254902	58.384125	3.9725006	18.108713								
T0	#9B8466	Sorrell Brown	155	132	102	33.96226	0.3419355	0.60784316	33.962257	0.20948619	0.50392157	56.51715	4.18964	19.466793								
Average T0			154.7	132	103.7	33.3207533	0.32991141	0.60653596	33.320739	0.20536593	0.506535957	56.514096	4.2768815	18.517394								
SD T0			4.509	5	4.726	0.81770906	0.01405111	0.01768334	0.81772306	0.00486423	0.017791701	1.8715574	0.3561087	0.8248495								
Error T0			2.915	3.788	4.559	2.45405333	4.25905644	2.91546421	2.45409642	2.36856652	3.51242614	3.3116647	8.326364	4.4544579								

Figure 49: Colour Calculations

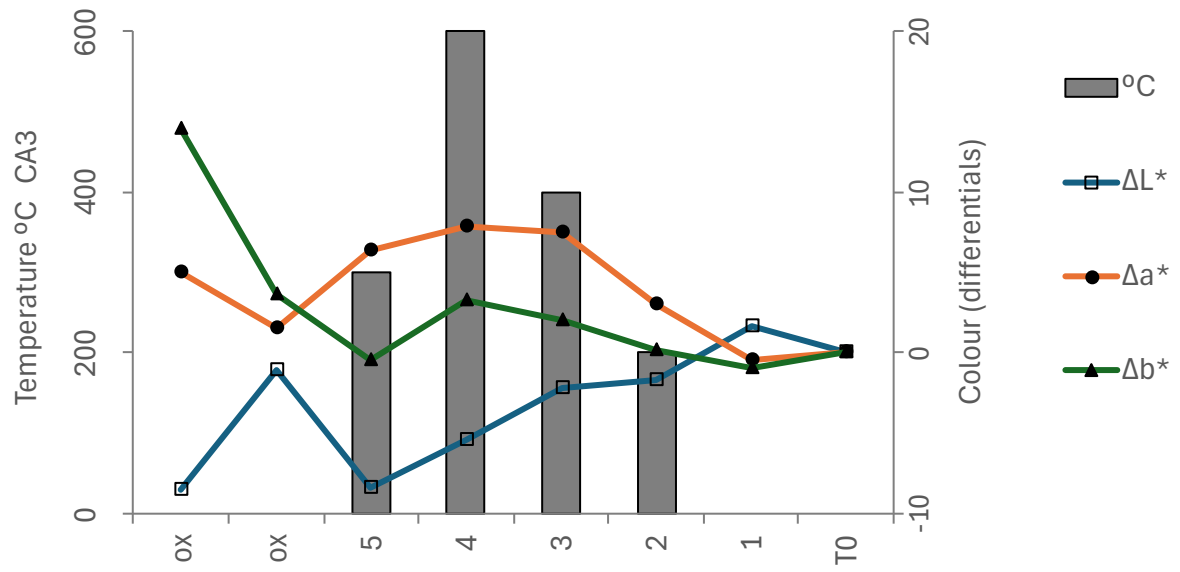


Figure 50: Colour Calculations Graphic

Supplementary Information 3- Chapter 5

Appendix 1: Sediment Preparation

- Sediment mix = 1 bucket volume of clay mixed with 4 volumes of sandy sediment
- Mixed within a cement mixer with stones (to break up larger chunks) for 1 hours
 - After 30 minutes the mixing is stopped and we removed the sand stuck in the back of the mixer.
- After 1 hour of mixing the sediment reached a stage with little beads of clay/sand aggregates 5-20mm in size
- This sediment was dried for 3 days and then remixed for 30 minute to remove the aggregates.
- After the 30 mins the sediment was subdivided in half and mixed for 1 hour.
- After 1 hour of additional mixing the beads were nearly completely removed leaving only a rare aggregates 1-3mm in size.

Appendix 2: FTIR Spectra

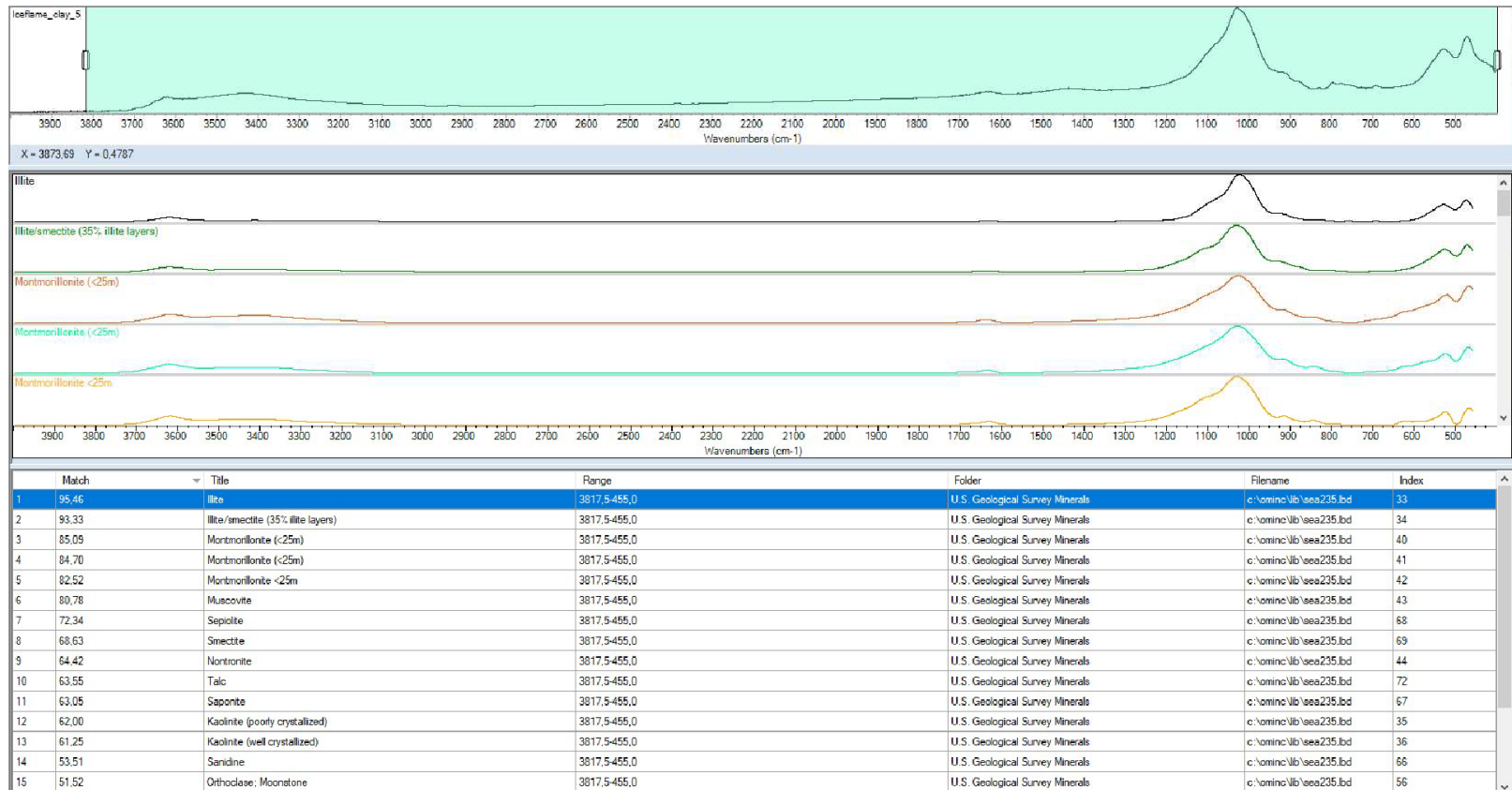


Figure 51: Clay FTIR Spectra with USGS library spectra matching

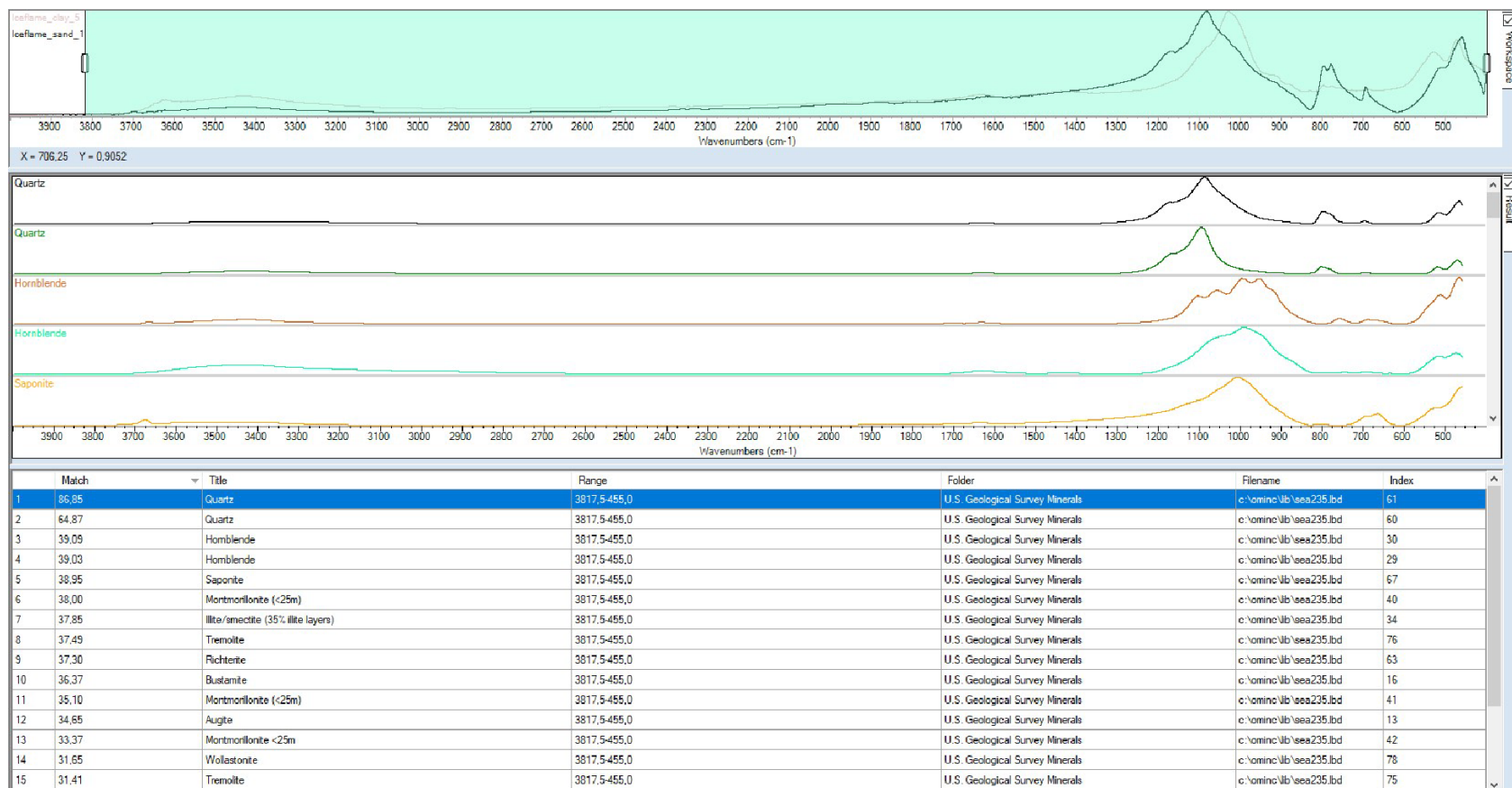


Figure 52: Sand FTIR Spectra with USGS library spectra matching

Mixed Sediment spectra:

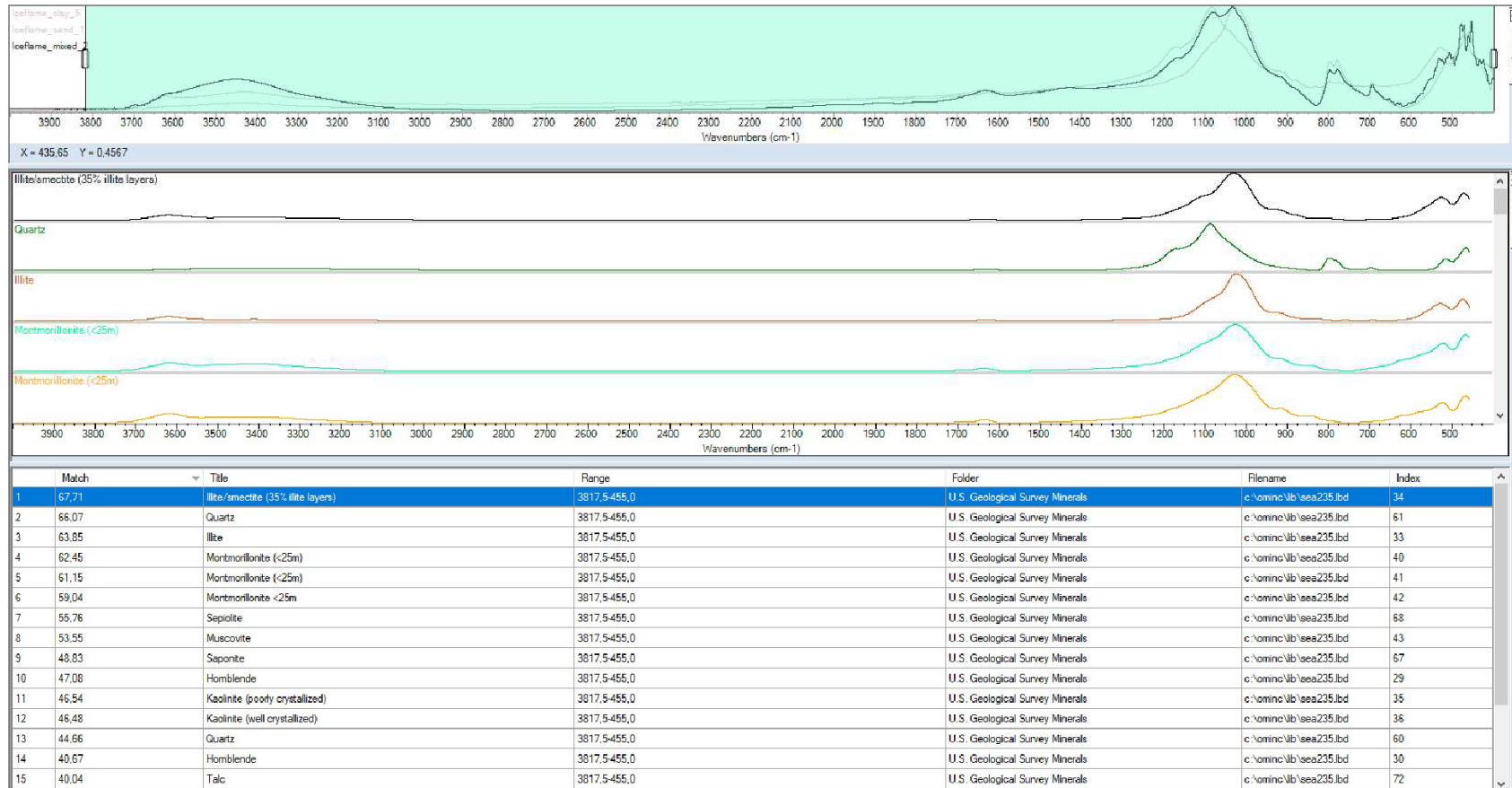


Figure 53: Mixed experimental sediment with USGS library spectra matching

Appendix 3: Moisture content protocol and results

Moisture content was calculated by placing 500g of completely dry sediment within a bottomless cylinder with filter (stocking) placed at the base. The set up was placed over a graduated cylinder to collect excess water. We then added a 150 ml of water to the sediment and allowed the excess water to be filtered out through stocking at the base of the cylinder. The results were calculated using mass (dry -wet weight) shown in Figure (XX) and subtraction (total water added- excess water) shown in Figure (XX). This protocol was repeated 5 times. We then used the average between the two methods equalling approx. 118 ml per 500 g of sediment as the standardized amount of water for 100% moisture content (50% = 118 ml /2).

Table 10: Mass method results

Sample ID	Cylinder weight	Dry weight sediment	Total dry weight	Wet Weight	Moisture content (method by mass)	Moisture content for 500g of dry sediment (method by mass)	Moisture content for 1kg of dry sediment (method by mass)
1	316.9	498.2	815.1	927.7	112.6	113.0	226.0
2	312.6	500	812.6	918	105.4	105.4	210.8
3	316.8	499.2	816	935.3	119.3	119.5	239.0
4	317	500.1	817.1	946.4	129.3	129.3	258.5
5	314.4	499.1	813.5	933	119.5	119.7	239.4
					Result	117.4	234.8
					STDEV	8.9	17.7
					Error		7.9

Table 11: Subtractive method results

Sample ID	Initial Water	Excess water	Remaining Moisture Content (Subtractive method)	Moisture content for 500g of dry sediment (Subtractive)	Moisture content for 1kg of dry sediment (Subtractive)
1	150	37	113	113.4	227.6
2	150	40	110	110.0	220.0
3	150	29	121	121.2	242.8
4	150	20	130	130.0	259.9
5	150	28.5	121.5	121.7	243.9
	Result	30.9	119.1	119.3	238.8
	STDEV	7.9	7.9	7.8	15.5
	Error			3.5	6.9

Appendix 4: Cylinder assembly protocol

1. Prepare, clean and dry experimental cylinder
2. Weight and tare aluminium container

For Buried Combustion features:

3. Add 500g of dried experimental sediment to the aluminium container
4. Pour 500 g of sediment into the cylinder.
5. Level sediment inside the cylinder
6. Add water using 50ml pipet
 - a. For 100% saturation – 118 ml of Water
 - b. For 50% saturation – 59 ml of water
7. add 20g of charcoal into a separate aluminium container.
8. pour the 20g of charcoal into the cylinder over the experimental substrate
9. level the charcoal layer
10. add 20g of ash into a separate aluminium container
11. pour 20g of ash into the cylinder over the charcoal layer
12. level the ash layer
13. add 500g of experimental sediment into the aluminium container

14. pour 500g of sediment over the ash layer using a 2mm screen to minimize the disruption to the underlying ash.

15. Level the sediment layer

16. Add water following description in 6.

For Surface Combustion Features:

3. Repeat steps 3-6 outlined above resulting in 500g of sediment in the cylinder.

4. Repeat steps 3-6 outlined above resulting in a layer of 1000g of sediment in the cylinder.

5. Repeat steps 7-12 outlined above resulting in a layer of charcoal then ash exposed to the surface.

Appendix 5: Measurement data

Table 12: Average thickness and variability (as represented by the coefficient of variation) for different substrate samples. Data include position (B=Buried, S= Surface), moisture content (1 = 100%, 0.5 = 50%, 0 = dry), number of freeze-thaw cycles, and time frozen (in hours). Measurements were taken for ash (A) and charcoal (C) layers, where the average values represent layer thickness, and the coefficient of variation (CV) indicates the regularity of the layer's structure.

Sample ID	Position	Layer	Moisture content	Number of cycles	Time frozen (hours)	Avg	St.dev	CV
101	B	A	1	60	1290	7.15	1.57	0.22
101	B	C	1	60	1290	6.63	0.79	0.12
102	B	A	1	60	1290	6.81	0.56	0.08
102	B	C	1	60	1290	5.91	0.86	0.15
103	B	A	1	60	1290	3.53	0.63	0.18
103	B	C	1	60	1290	5.58	0.76	0.14
104	B	A	1	0	0	7.01	1.22	0.17
104	B	C	1	0	0	6.79	0.58	0.09
105	B	A	1	0	0	4.96	0.63	0.13
105	B	C	1	0	0	7.18	0.62	0.09

106	B	A	1	0	0	5.34	0.48	0.09
106	B	C	1	0	0	7.73	0.73	0.09
107	B	A	0.5	60	1290	5.02	0.88	0.17
107	B	C	0.5	60	1290	7.86	0.89	0.11
108	B	A	0.5	60	1290	4.63	0.88	0.19
108	B	C	0.5	60	1290	8.17	0.80	0.10
109	B	A	0.5	60	1290	4.96	0.71	0.14
109	B	C	0.5	60	1290	7.33	1.28	0.17
110	B	A	0.5	0	0	4.86	0.81	0.17
110	B	C	0.5	0	0	7.45	1.53	0.21
111	B	A	0.5	0	0	5.58	1.19	0.21
111	B	C	0.5	0	0	6.34	1.07	0.17
112	B	A	0.5	0	0	5.72	0.49	0.09
112	B	C	0.5	0	0	7.32	0.96	0.13
113	B	A	0	60	1290	4.78	0.33	0.07
113	B	C	0	60	1290	10.58	1.11	0.10
114	B	A	0	60	1290	6.74	0.51	0.08
114	B	C	0	60	1290	6.67	2.47	0.37

115	B	A	0	60	1290	5.49	0.61	0.11
115	B	C	0	60	1290	7.50	0.53	0.07
116	B	A	0	0	0	6.05	1.38	0.23
116	B	C	0	0	0	6.30	1.37	0.22
117	B	A	0	0	0	5.25	1.00	0.19
117	B	C	0	0	0	7.09	1.20	0.17
118	B	A	0	0	0	4.88	0.62	0.13
118	B	C	0	0	0	6.01	0.59	0.10
119	S	A	1	60	1290	3.99	3.22	0.81
119	S	C	1	60	1290	9.94	0.81	0.08
120	S	A	1	60	1290	4.41	4.66	1.06
120	S	C	1	60	1290	9.93	1.88	0.19
121	S	A	1	60	1290	4.10	2.78	0.68
121	S	C	1	60	1290	8.36	4.03	0.48
122	S	A	1	0	0	6.67	1.67	0.25
122	S	C	1	0	0	10.00	2.04	0.20
123	S	A	1	0	0	6.03	0.66	0.11
123	S	C	1	0	0	11.81	0.72	0.06

124	S	A	1	0	0	6.95	1.23	0.18
124	S	C	1	0	0	9.55	1.12	0.12
125	S	A	0.5	60	1290	6.78	1.21	0.18
125	S	C	0.5	60	1290	9.08	2.03	0.22
126	S	A	0.5	60	1290	3.04	1.62	0.53
126	S	C	0.5	60	1290	9.64	0.26	0.03
127	S	A	0.5	60	1290	3.51	3.02	0.86
127	S	C	0.5	60	1290	11.85	2.11	0.18
128	S	A	0.5	0	0	6.88	1.11	0.16
128	S	C	0.5	0	0	9.56	0.93	0.10
129	S	A	0.5	0	0	6.66	0.78	0.12
129	S	C	0.5	0	0	10.43	1.10	0.11
130	S	A	0.5	0	0	7.25	1.49	0.21
130	S	C	0.5	0	0	9.98	1.28	0.13
131	S	A	0	60	1290	6.80	1.06	0.16
131	S	C	0	60	1290	6.94	1.13	0.16
132	S	A	0	60	1290	5.42	0.85	0.16
132	S	C	0	60	1290	9.78	1.19	0.12

133	S	A	0	60	1290	6.26	0.78	0.12
133	S	C	0	60	1290	8.77	2.50	0.28
134	S	A	0	0	0	6.15	0.51	0.08
134	S	C	0	0	0	6.73	0.61	0.09
135	S	A	0	0	0	6.43	0.61	0.09
135	S	C	0	0	0	8.53	1.27	0.15
136	S	A	0	0	0	6.19	0.99	0.16
136	S	C	0	0	0	6.52	0.74	0.11
139	B	A	1	30	423	5.67	1.41	0.25
139	B	C	1	30	423	7.31	0.57	0.08
140	B	A	1	30	423	5.32	1.36	0.26
140	B	C	1	30	423	7.99	1.36	0.17
141	B	A	1	30	423	5.42	1.72	0.32
141	B	C	1	30	423	8.16	1.32	0.16
142	S	A	1	30	423	5.54	3.46	0.62
142	S	C	1	30	423	10.63	0.73	0.07
143	S	A	1	30	423	6.92	1.42	0.20
143	S	C	1	30	423	6.76	0.67	0.10

144	S	A	1	30	423	6.70	0.79	0.12
144	S	C	1	30	423	8.39	0.90	0.11
145	B	A	1	1	1290	5.03	0.59	0.12
145	B	C	1	1	1290	6.63	0.31	0.05
146	B	A	1	1	1290	6.05	1.26	0.21
146	B	C	1	1	1290	6.71	0.46	0.07
147	B	A	1	1	1290	4.64	0.44	0.10
147	B	C	1	1	1290	8.00	1.25	0.16
148	S	A	1	1	1290	8.58	1.12	0.13
148	S	C	1	1	1290	8.15	1.17	0.14
149	S	A	1	1	1290	8.82	1.06	0.12
149	S	C	1	1	1290	8.49	1.29	0.15
150	S	A	1	1	1290	7.18	2.18	0.30
150	S	C	1	1	1290	9.33	0.49	0.05
151	B	A	1	10	158	5.47	0.83	0.15
151	B	C	1	10	158	6.62	0.93	0.14
152	B	A	1	10	158	5.41	1.23	0.23
152	B	C	1	10	158	7.06	1.05	0.15

153	B	A	1	10	158	5.75	0.98	0.17
153	B	C	1	10	158	7.05	1.12	0.16
154	B	A	1	1	16	6.21	0.79	0.13
154	B	C	1	1	16	6.17	1.18	0.19
155	B	A	1	1	16	6.23	1.55	0.25
155	B	C	1	1	16	7.17	0.70	0.10
156	B	A	1	1	16	5.63	0.73	0.13
156	B	C	1	1	16	7.50	1.15	0.15
157	S	A	1	10	158	7.35	1.26	0.17
157	S	C	1	10	158	10.41	1.15	0.11
158	S	A	1	10	158	5.69	3.25	0.57
158	S	C	1	10	158	10.83	1.16	0.11
159	S	A	1	10	158	6.90	1.06	0.15
159	S	C	1	10	158	9.74	1.27	0.13
160	S	A	1	1	16	7.47	1.87	0.25
160	S	C	1	1	16	8.58	1.09	0.13
161	S	A	1	1	16	7.45	2.64	0.35
161	S	C	1	1	16	10.00	1.62	0.16

162	S	A	1	1	16	6.18	0.44	0.07
162	S	C	1	1	16	11.08	1.03	0.09

Appendix 6: R code for statistical analysis

```
View(Macrodata_Update_CM)
Macrodata_Update_CM <- read_excel("")
View(Macrodata_Update_CM)
Iceflame_Macro <- as.data.frame(Macrodata_Update_CM)
View(Iceflame_Macro)
head(Iceflame_Macro)
summary(Iceflame_Macro)
library(ggplot2)
library(ggpubr)
library(officer)
library (flextable)
##### Effect of number of cycles and moisture content on average
thickness and irregularity

####Thickness####
DataCy060<- subset(Macrodata_Update_CM, Nb_Cy %in% c(0,60))
DataCy060$Nb_Cy<-as.factor(DataCy060$Nb_Cy)
is.factor(DataCy060$Nb_Cy)

ancova_3<-aov(avg~Position:Layer:Water:Nb_Cy, data=DataCy060)

hist(ancova_3$residuals)# residulas are normally distributed remove
plot(ancova_3$residuals,ancova_3$fitted.values)# no bias, no outlier
summary(ancova_3)# there is something, let's dissectate the Ancova

ancova_4<-aov(avg~Position*Layer*Water*Nb_Cy, data=DataCy060)
summary(ancova_4) # The quadruple interaction is NS, let's adopt a backward step-by-
step approach

ancova_5<-aov(avg~Position + Layer+ Water+ Nb_Cy
```

```

+ Position:Layer:Water
+ Position:Layer:Nb_Cy
+ Position:Water:Nb_Cy
+ Layer:Water:Nb_Cy
, data=DataCy060)

hist(ancova_5$residuals)# residulas are normally distributed
plot(ancova_5$residuals,ancova_5$fitted.values)
summary(ancova_5)# Layer:Water:Nb_Cy is NS, we delete it

ancova_6<-aov(avg~Position + Layer+ Water+ Nb_Cy
+ Position:Layer:Water
+ Position:Layer:Nb_Cy
+ Position:Water:Nb_Cy
, data=DataCy060)

hist(ancova_6$residuals)# residulas are normally distributed
plot(ancova_6$residuals,ancova_6$fitted.values)
summary(ancova_6)# , we delete it

### create table for word doc
summary_text <- capture.output(summary(ancova_6))
summary_df <- data.frame(Output = summary_text)
write.csv(summary_df, file = "Avg_Nb_CyXwater.csv", row.names = FALSE)

#### ANOVA to look a relationship between subset data on thickness
DataCy060SA<-subset(DataCy060, Position == "S" & Layer == "A")
DataCy060SC<-subset(DataCy060, Position == "S" & Layer == "C")
DataCy060BA<-subset(DataCy060, Position == "B" & Layer == "A")
DataCy060BC<-subset(DataCy060, Position == "B" & Layer == "C")
Anova060SA<-aov(avg~Water*Nb_Cy, data= DataCy060SA)
Anova060SC<-aov(avg~Water*Nb_Cy, data= DataCy060SC)

```

```

Anova060BA<-aov(avg~Water*Nb_Cy, data= DataCy060BA)
Anova060BC<-aov(avg~Water*Nb_Cy, data= DataCy060BC)
hist(Anova060SA$residuals)
plot(Anova060SA$residuals, Anova060SA$fitted.values)

summary(Anova060SA)
summary(Anova060SC)
summary(Anova060BA)
summary(Anova060BC)

summary_060SA <- capture.output(summary(Anova060SA))
summary_df060SA <- data.frame(Output = summary_060SA)
write.csv(summary_df060SA, file = "Avg_060SA.csv", row.names = FALSE)

summary_060SC <- capture.output(summary(Anova060SC))
summary_df060SC <- data.frame(Output = summary_060SC)
write.csv(summary_df060SC, file = "Avg_060SC.csv", row.names = FALSE)

summary_060BA <- capture.output(summary(Anova060BA))
summary_df060BA <- data.frame(Output = summary_060BA)
write.csv(summary_df060BA, file = "Avg_060BA.csv", row.names = FALSE)

summary_060BC <- capture.output(summary(Anova060BC))
summary_df060BC <- data.frame(Output = summary_060BC)
write.csv(summary_df060BC, file = "Avg_060BC.csv", row.names = FALSE)

hist(Anova060BC$residuals)
plot(Anova060BC$residuals, Anova060BC$fitted.values)
plot(DataCy060BC$Water, DataCy060BC$avg, col=(1, "Nb_Cy"))

```

```
#####graphics for Avg Thickness
```

```

library(ggplot2)
library(ggpubr)

avsa060<-ggplot(DataCy060SA, aes(x=Water, y=avg, colour = Nb_Cy, shape = Nb_Cy))+
geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+ ylim( 2,12)+
labs(title = "Thickness of the Surface Ash", x = "Water Saturation", y="Thickness") +
theme_minimal()+
theme(legend.position = "right")

avsc060<-ggplot(DataCy060SC, aes(x=Water, y=avg, colour = Nb_Cy, shape = Nb_Cy))+
geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+ ylim( 2,12)+
labs(title = "Thickness of the Surface Charcoal", x = "Water Saturation", y="Thickness") +
theme_minimal()+
theme(legend.position = "right")

avba060<-ggplot(DataCy060BA, aes(x=Water, y=avg, colour = Nb_Cy, shape = Nb_Cy))+
geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+ ylim( 2,12)+
labs(title = "Thickness of the Buried Ash", x = "Water Saturation", y="Thickness") +
theme_minimal()+
theme(legend.position = "right")

avbc060<-ggplot(DataCy060BC, aes(x=Water, y=avg, colour = Nb_Cy, shape = Nb_Cy))+
geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+ ylim( 2,12)+
labs(title = "Thickness of the Buried Charcoal", x = "Water Saturation", y="Thickness") +
theme_minimal()+
theme(legend.position = "right")

figure1 <- ggarrange(avsa060, avsc060, avba060, avbc060,
                    ncol = 2, nrow = 2)

```

figure1

```
####CofVariance or Irregularity####
```

```
####notes: log10 for cofvar and repeat same type as above grouping by position and layer.
```

```
ancova_3cofv<-aov(log10(cofvariation)~Position:Layer:Water:Nb_Cy, data=DataCy060)
```

```
hist(ancova_3cofv$residuals)# residulas are normally distributed
```

```
plot(ancova_3cofv$residuals,ancova_3cofv$fitted.values)
```

```
summary(ancova_3cofv)
```

```
ancova_4cofv<-aov(log10(cofvariation)~Position*Layer*Water*Nb_Cy, data=DataCy060)
```

```
summary(ancova_4cofv) # the quadruple interact is NS so work backwards like above
```

```
###
```

```
ancova_5cofv<-aov(log10(cofvariation)~Position + Layer+ Water+ Nb_Cy
```

```
  + Position:Layer:Water
```

```
  + Position:Layer:Nb_Cy
```

```
  + Position:Water:Nb_Cy
```

```
  + Layer:Water:Nb_Cy
```

```
  , data=DataCy060)
```

```
hist(ancova_5cofv$residuals)# residuals are normally distributed
```

```
plot(ancova_5cofv$residuals,ancova_5cofv$fitted.values)
```

```
summary(ancova_5cofv)
```

```
print(ancova_5cofv)
```

```
####create table for Word doc
```

```
summary_textcofv <- capture.output(summary(ancova_5cofv))
```

```
summary_dfcofv <- data.frame(Output = summary_textcofv)
```

```
write.csv(summary_dfcofv, file = "CofV_Nb_CyXwater.csv", row.names = FALSE)
```

```
##### ANOVA on subset data Log10(cofvariation)
```

```
Anova060covSA<-aov(log10(cofvariation)~Water*Nb_Cy, data= DataCy060SA)
```

```
Anova060covSC<-aov(log10(cofvariation)~Water*Nb_Cy, data= DataCy060SC)
```

```
Anova060covBA<-aov(log10(cofvariation)~Water*Nb_Cy, data= DataCy060BA)
```

```
Anova060covBC<-aov(log10(cofvariation)~Water*Nb_Cy, data= DataCy060BC)
```

```
hist(Anova060covSA$residuals)
```

```
plot(Anova060covSA$residuals, Anova060covSA$fitted.values)
```

```
summary(Anova060covSA)
```

```
summary(Anova060covSC)
```

```
summary(Anova060covBA)
```

```
summary(Anova060covBC)
```

```
summary_060covSA <- capture.output(summary(Anova060covSA))
```

```
summary_df060covSA <- data.frame(Output = summary_060covSA)
```

```
write.csv(summary_df060covSA, file = "COFV_060SA.csv", row.names = FALSE)
```

```
summary_060covSC <- capture.output(summary(Anova060covSC))
```

```
summary_df060covSC <- data.frame(Output = summary_060covSC)
```

```
write.csv(summary_df060covSC, file = "COFV_060SC.csv", row.names = FALSE)
```

```
summary_060covBA <- capture.output(summary(Anova060covBA))
```

```
summary_df060covBA <- data.frame(Output = summary_060covBA)
```

```
write.csv(summary_df060BA, file = "COFV_060BA.csv", row.names = FALSE)
```

```
summary_060covBC <- capture.output(summary(Anova060covBC))
```

```
summary_df060covBC <- data.frame(Output = summary_060covBC)
```

```
write.csv(summary_df060covBC, file = "COFV_060BC.csv", row.names = FALSE)
```

```
##### graphic for irregularity
```

```
covsa060<-ggplot(DataCy060SA, aes(x=Water, y=log10(cofvariation), colour = Nb_Cy,
shape = Nb_Cy))+ geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE) +
ylim(-1.5, 0.5) + theme_minimal() +
labs(title = "Regularity of the Surface Ash", x = "Water Saturation", y="Regularity") +
theme_minimal()+
theme(legend.position = "right")
```

```
covsc060<-ggplot(DataCy060SC, aes(x=Water, y=log10(cofvariation), colour = Nb_Cy,
shape = Nb_Cy))+ geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+
ylim(-1.5, 0.5)+ theme_minimal()+
labs(title = "Regularity of the Surface Charcoal", x = "Water Saturation", y="Regularity") +
theme_minimal()+
theme(legend.position = "right")
```

```
covba060<-ggplot(DataCy060BA, aes(x=Water, y=log10(cofvariation), colour = Nb_Cy,
shape = Nb_Cy))+ geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+
ylim(-1.5, 0.5)+ theme_minimal()+
labs(title = "Regularity of the Buried Ash", x = "Water Saturation", y="Regularity") +
theme_minimal()+
theme(legend.position = "right")
```

```
covbc060<-ggplot(DataCy060BC, aes(x=Water, y=log10(cofvariation), colour = Nb_Cy,
shape = Nb_Cy))+ geom_point(aes(Water, colour = Nb_Cy)) +
geom_smooth(method = "lm", fullrange=TRUE)+
ylim(-1.5, 0.5)+ theme_minimal()+
```

```
labs(title = "Regularity of the Buried Charcoal", x = "Water Saturation", y="Regularity") +
theme_minimal()+
theme(legend.position = "right")
```

```
figure2 <- ggarrange(covsa060, covsc060, covba060, covbc060,
                    ncol = 2, nrow = 2)
```

figure2

```
##### Effect of Number of cycles on Thickness and irregularity, all moisture is
100%
```

```
### Data Prep###
```

```
DataNbcy_1 <- subset(Iceflame_Macro, Water == "1")
```

```
dim(DataNbcy_1)
```

```
head(DataNbcy_1)
```

```
View(DataNbcy_1)
```

```
####Thickness####
```

```
ancova_1 <- aov(avg~Layer:Position:Nb_Cy, data = DataNbcy_1)
```

```
hist(ancova_1$residuals)#residuals look normally distributed
```

```
plot(ancova_1$residuals, ancova_1$fitted.values) ## no outlier, no bias in the distribution
of res
```

```
summary(ancova_1) ## ANCOVA is significant, let's dissect it.
```

```
ancova_2<-aov(avg~Layer*Position*Nb_Cy,data = DataNbcy_1)
```

```
summary(ancova_2)
```

```
#### create table for word doc
```

```
summary_textnbcy <- capture.output(summary(ancova_2))
```

```
summary_dfnbcy <- data.frame(Output = summary_textnbcy)
```

```
write.csv(summary_dfnbcy, file = "Avg_NB_CY_water1.csv", row.names = FALSE)
```

```
### Let's test the 4 relationship between NbCy and AvgThickness, for BA, BC, SA, SC.
```

```
## a. let's create the subset of data
```

```
SAdata<-subset(DataNbcy_1, Layer=="A"& Position=="S")
```

```
SCdata<-subset(DataNbcy_1, Layer=="C"& Position=="S")
```

```
BAdata<-subset(DataNbcy_1, Layer=="A"& Position=="B")
```

```
BCdata<-subset(DataNbcy_1, Layer=="C"& Position=="B")
```

```
##b. Spearman non-parametric correlation to test the relationship for each possibility
```

```
corSA<-cor.test(SAdata$Nb_Cy, SAdata$avg, method="spearman")
```

```
corSC<-cor.test(SCdata$Nb_Cy, SCdata$avg, method="spearman")
```

```
corBA<-cor.test(BAdata$Nb_Cy, BAdata$avg, method="spearman")
```

```
corBC<-cor.test(BCdata$Nb_Cy, BCdata$avg, method="spearman")
```

```
corSA
```

```
corSC
```

```
corBA
```

```
corBC
```

```
##=>The layer of ash at the surface thins with the increasing number of cycles, whereas it does not affect the ash when buried or the charcoal
```

```
summary_textSAc <- capture.output(corSA)
```

```
summary_SAc <- data.frame(Output = summary_textSAc)
```

```
write.csv(summary_SAc, file = "Avg_SAcorl.csv", row.names = FALSE)
```

```
summary_textSCc <- capture.output(corSC)
```

```
summary_SCc <- data.frame(Output = summary_textSCc)
```

```
write.csv(summary_SCc, file = "Avg_SCcorl.csv", row.names = FALSE)
```

```
summary_textBAc <- capture.output(corBA)
```

```
summary_BAc <- data.frame(Output = summary_textBAc)
```

```
write.csv(summary_BAc, file = "Avg_BAcorl.csv", row.names = FALSE)
```

```
summary_textBCc <- capture.output(corBC)
summary_BCc <- data.frame(Output = summary_textBCc)
write.csv(summary_BCc, file = "Avg_BCcorl.csv", row.names = FALSE)
```

###I.C. Graphic representation

```
##### each graphic separated #####
avsacy <- ggplot(SAdata, aes(Nb_Cy,avg))+ geom_point()+
geom_smooth(method = "lm",color= "blue")+ ylim(2, 12) + ggtitle("Surface Ash")
avsacy
avscopy <- ggplot(SCdata, aes(Nb_Cy,avg))+ geom_point() +
geom_smooth(method = "lm",color= "blue")+ ylim(2, 12)+ ggtitle("Surface Charcoal")
avbacy <- ggplot(BAdata, aes(Nb_Cy,avg))+ geom_point() +
geom_smooth(method = "lm",color= "blue")+ ylim(2, 12)+ ggtitle("Buried Ash")
avbccy <- ggplot(BCdata, aes(Nb_Cy,avg))+ geom_point() +
geom_smooth(method = "lm",color= "blue")+ ylim(2, 12)+ ggtitle("Buried Charcoal")
```

```
##### combined graphic for f(Nb_Cy)- only saturated ##
AVGNbcy_1 <- ggplot(DataNbcy_1, aes( x= Nb_Cy, y=avg,color= interaction(Position,
Layer, sep = "")),
      group = interaction ( Position, Layer, sep = ":",)) + geom_point()+
geom_smooth( method = lm)+
labs(title = "Thickness of the layer by the number of cycles", x = "Number of cycles
(0,1,10,30,60)", y="Thickness", color= "Type") +
theme_minimal()+
theme(legend.position = "bottom")
```

```
View(AVGNbcy_1)
```

```
#### Irregularity ####
```

```
ancova_1cofv <- aov(cofvariation~Layer:Position:Nb_Cy, data = DataNbcy_1)
hist(ancova_1cofv$residuals)
plot(ancova_1cofv$residuals, ancova_1cofv$fitted.values) ## no outlier, no bias in the
distribution of res
summary(ancova_1cofv) ## ANCOVA is significant, let's dissect it.
```

```
ancova_l1cofv <- aov(log10(cofvariation)~Layer:Position:Nb_Cy, data = DataNbcy_1)
hist(ancova_l1cofv$residuals)#residuals look normally distributed
plot(ancova_l1cofv$residuals, ancova_l1cofv$fitted.values)
summary(ancova_l1cofv)
```

```
plot(DataNbcy_1$cofvariation,log10(DataNbcy_1$cofvariation))
hist(log10(DataNbcy_1$cofvariation))
ancova_l2cofv<-aov(log10(cofvariation)~Layer*Position*Nb_Cy,data = DataNbcy_1)
summary(ancova_l2cofv)
ancova_l3cofv<-
aov(log10(cofvariation)~Position*Nb_Cy+Layer*Position+Layer*Nb_Cy,data =
DataNbcy_1)
summary(ancova_l3cofv)
```

```
ancova_l4cofv<-aov(log10(cofvariation)~Position*Nb_Cy+Layer*Position,data =
DataNbcy_1)
hist(ancova_l4cofv$residuals)
summary(ancova_l4cofv)
```

```
##### report this one in the si
```

```
ancova_l5cofv<-aov(log10(cofvariation)~Position*Nb_Cy+Layer,data = DataNbcy_1)
hist(ancova_l5cofv$residuals)#residuals look normally distributed
plot(ancova_l5cofv$residuals, ancova_l5cofv$fitted.values)# residuals are homogeneously
distributed
```

summary(ancova_15cofv)# see what's in ANCOVA: regardless of position and nb of cycles, layers are different. In addition, the regularity does not behave the same with increasing number of cycle depending on the position.

Export to excel

```
summary_textcofvnbcy <- capture.output(summary(ancova_15cofv))
summary_dfcofvnbcy <- data.frame(Output = summary_textcofvnbcy)
write.csv(summary_dfcofvnbcy, file = "Cofv_NB_CY_water1.csv", row.names = FALSE)
```

regularity of the layer graphic#####

```
COVNbcy_1 <- ggplot(DataNbcy_1, aes( x= Nb_Cy, y=log10(cofvariation),color=
interaction(Position, Layer, sep = ""),
          group = interaction ( Position, Layer, sep = ":"))) +
  geom_point()+
  geom_smooth( method = lm) +
  labs(title = "Regularity of the layer by the number of cycles", x = "Number of cycles
(0,1,10,30,60)", y="Regularity", color= "Type") +
  theme_minimal()+
  theme(legend.position = "bottom")
```

```
COVNbcy_12 <- ggplot(DataNbcy_1, aes( x= Nb_Cy, y=log10(cofvariation),color=
Position)) +
  geom_point()+
  geom_smooth( method = lm) +
  labs(title = "Regularity of the layer by the number of cycles", x = "Number of cycles
(0,1,10,30,60)", y="Regularity", color= "Type") +
  theme_minimal()+
  theme(legend.position = "bottom")
```

COVNbcy_12

#==>The regularity of the layer of ash at the surface changes with the increasing number of cycles, whereas it does not affect the ash when buried or the charcoal

###I.C. Graphic representation

Figure avg and cov combined#####

```
figNbcy_1 <- ggarrange(AVGNbcy_1,COVNbcy_1,ncol = 1, nrow = 2, )
```

```
figNbcy_1
```

Effect on Time frozen on Average thickness and Irregularity

###Data prep###

```
DataTime <- subset(Iceflame_Macro, Water == "1")
```

```
as.factor(DataTime$Nb_Cy)
```

```
DataTime1<-subset(DataTime, Nb_Cy== "1")
```

```
DataTime60<-subset(DataTime, Nb_Cy== "60")
```

```
DataTime160<-rbind.data.frame(DataTime1, DataTime60)
```

```
head(DataTime160)
```

Thickness

```
anovotime <- aov(avg~Nb_Cy:Time_frozen:Position:Layer, data = DataTime160)
```

```
hist(anovotime$residuals)
```

```
plot(anovotime$residuals, anovotime$fitted.values)
```

summary(anovotime) ##### four way interaction is highly significant so we need to see the relationship between different factors based on Pos and Layer

```
summary_textavgtime <- capture.output(summary(anovotime))
```

```
summary_dfavgtime <- data.frame(Output = summary_textavgtime)
```

```
write.csv(summary_dfavgtime, file = "Avg_Time.csv", row.names = FALSE)
```

```

DataTime160SA<-subset(DataTime160, Position == "S" & Layer == "A")
DataTime160SC<-subset(DataTime160, Position == "S" & Layer == "C")
DataTime160BA<-subset(DataTime160, Position == "B" & Layer == "A")
DataTime160BC<-subset(DataTime160, Position == "B" & Layer == "C")
AnovatetimeSA<-aov(avg~Time_frozen+Nb_Cy, data= DateTime160SA)
AnovatetimeSC<-aov(avg~Time_frozen+Nb_Cy, data= DateTime160SC)
AnovatetimeBA<-aov(avg~Time_frozen+Nb_Cy, data= DateTime160BA)
AnovatetimeBC<-aov(avg~Time_frozen+Nb_Cy, data= DateTime160BC)
hist(AnovatetimeSA$residuals)
plot(AnovatetimeSA$residuals, AnovatetimeSA$fitted.values)
summary(AnovatetimeSA)
summary(AnovatetimeSC)
summary(AnovatetimeBA)
summary(AnovatetimeBC)

summary_textavgtimeSA <- capture.output(summary(AnovatetimeSA))
summary_dfavgtimeSA <- data.frame(Output = summary_textavgtimeSA)
write.csv(summary_dfavgtimeSA, file = "Avg_TimeSA.csv", row.names = FALSE)

summary_textavgtimeSC <- capture.output(summary(AnovatetimeSC))
summary_dfavgtimeSC <- data.frame(Output = summary_textavgtimeSC)
write.csv(summary_dfavgtimeSC, file = "Avg_TimeSC.csv", row.names = FALSE)

summary_textavgtimeBA <- capture.output(summary(AnovatetimeBA))
summary_dfavgtimeBA <- data.frame(Output = summary_textavgtimeBA)
write.csv(summary_dfavgtimeBA, file = "Avg_TimeBA.csv", row.names = FALSE)

summary_textavgtimeBC <- capture.output(summary(AnovatetimeBC))
summary_dfavgtimeBC <- data.frame(Output = summary_textavgtimeBC)
write.csv(summary_dfavgtimeBC, file = "Avg_TimeBC.csv", row.names = FALSE)

```

```
##### graphics for time avg
```

```
DataTime160F <- DataTime160
```

```
DataTime160F$Nb_Cy<-as.factor(DataTime160F$Nb_Cy)
```

```
DataTime160F$Time_frozen<-as.factor(DataTime160F$Time_frozen)
```

```
is.factor(DataTime160F$Nb_Cy)
```

```
DataTime160FSA<-subset(DataTime160F, Position == "S" & Layer == "A")
```

```
DataTime160FSC<-subset(DataTime160F, Position == "S" & Layer == "C")
```

```
DataTime160FBA<-subset(DataTime160F, Position == "B" & Layer == "A")
```

```
DataTime160FBC<-subset(DataTime160F, Position == "B" & Layer == "C")
```

```
ggplot(DataTime160FSA,aes(y=avg, colour = interaction(Nb_Cy, Time_frozen)))+  
geom_boxplot(aes(x=Nb_Cy)) +
```

```
  geom_point(aes(Nb_Cy))+ geom_boxplot(aes(x=Time_frozen))+  
  geom_point(aes(Time_frozen))+
```

```
  theme(legend.position = "bottom")
```

```
a160F<-ggplot(DataTime160FSA,aes(interaction(Nb_Cy, Time_frozen),avg, colour =  
interaction(Nb_Cy, Time_frozen)))+
```

```
  geom_boxplot() + geom_point()+ ylim(3, 12)+
```

```
  labs(title = "Surface Ash", x = "Number of cycles. Time frozen", y="Thickness") +
```

```
  theme_minimal()+
```

```
  theme(legend.position = "bottom")
```

```
b160F<-ggplot(DataTime160FSC,aes(interaction(Nb_Cy, Time_frozen),avg, colour =  
interaction(Nb_Cy, Time_frozen)))+
```

```
  geom_boxplot() + geom_point()+ylim(3, 12)+
```

```
  labs(title = "Surface Charcoal", x = "Number of cycles. Time frozen", y="Thickness") +
```

```
  theme_minimal()+
```

```
  theme(legend.position = "bottom")
```

```
c160F<-ggplot(DataTime160FBA,aes(interaction(Nb_Cy, Time_frozen),avg, colour =  
interaction(Nb_Cy, Time_frozen)))+
```

```
  geom_boxplot() + geom_point()+ylim(3, 12)+
```

```

  labs(title = "Buried Ash", x = "Number of cycles. Time frozen", y="Thickness") +
  theme_minimal()+
  theme(legend.position = "bottom")
d160F<-ggplot(DataTime160FBC,aes(interaction(Nb_Cy, Time_frozen),avg, colour =
interaction(Nb_Cy, Time_frozen)))+
  geom_boxplot() + geom_point()+ylim(3, 12)+
  labs(title = "Buried Charcoal", x = "Number of cycles. Time frozen", y="Thickness") +
  theme_minimal()+
  theme(legend.position = "bottom")

figure3 <- ggarrange(a160F, b160F, c160F, d160F,
  ncol = 2, nrow = 2)

```

figure3

####Irregularity####

```

anovacovtime <- aov(log10(cofvariation)~Nb_Cy:Time_frozen:Position:Layer, data =
DataTime160)
hist(anovacovtime$residuals)
plot(anovacovtime$residuals, anovacovtime$fitted.values)
summary(anovacovtime)

```

export to excel

```

summary_textcovtime <- capture.output(summary(anovacovtime))
summary_dfcovtime <- data.frame(Output = summary_textcovtime)
write.csv(summary_dfcovtime, file = "Cov_Time.csv", row.names = FALSE)

```

#####

```

AnovatetimeSAcov<-aov(log10(cofvariation)~Time_frozen+Nb_Cy, data= DataTime160SA)
AnovatetimeSCcov<-aov(log10(cofvariation)~Time_frozen+Nb_Cy, data= DataTime160SC)

```

```

AnovatetimeBAcov<-aov(log10(cofvariation)~Time_frozen+Nb_Cy, data= DateTime160BA)
AnovatetimeBCcov<-aov(log10(cofvariation)~Time_frozen+Nb_Cy, data= DateTime160BC)
hist(AnovatetimeSAcov$residuals)
plot(AnovatetimeSAcov$residuals, AnovatetimeSAcov$fitted.values)
summary(AnovatetimeSAcov)
summary(AnovatetimeSCcov)
summary(AnovatetimeBAcov)
summary(AnovatetimeBCcov)

summary_textcovtimeSA <- capture.output(summary(AnovatetimeSAcov))
summary_dfcovtimeSA <- data.frame(Output = summary_textcovtimeSA)
write.csv(summary_dfcovtimeSA, file = "COV_TimeSA.csv", row.names = FALSE)

summary_textcovtimeSC <- capture.output(summary(AnovatetimeSCcov))
summary_dfcovtimeSC <- data.frame(Output = summary_textcovtimeSC)
write.csv(summary_dfcovtimeSC, file = "COV_TimeSC.csv", row.names = FALSE)

summary_textcovtimeBA <- capture.output(summary(AnovatetimeBAcov))
summary_dfcovtimeBA <- data.frame(Output = summary_textcovtimeBA)
write.csv(summary_dfcovtimeBA, file = "COV_TimeBA.csv", row.names = FALSE)

summary_textcovtimeBC <- capture.output(summary(AnovatetimeBCcov))
summary_dfcovtimeBC <- data.frame(Output = summary_textcovtimeBC)
write.csv(summary_dfcovtimeBC, file = "COV_TimeBC.csv", row.names = FALSE)

##### graphics for COV time frozen
acov160F<-ggplot(DateTime160FSA,aes(interaction(Nb_Cy,
Time_frozen),log10(cofvariation), colour = interaction(Nb_Cy, Time_frozen)))+
  geom_boxplot() + geom_point()+ylim(-2, 1)+
  labs(title = "Surface Ash", x = "Number of cycles. Time frozen", y="Regularity") +

```

```

theme_minimal()+
theme(legend.position = "bottom")
bcov160F<-ggplot(DataTime160FSC,aes(interaction(Nb_Cy,
Time_frozen),log10(cofvariation), colour = interaction(Nb_Cy, Time_frozen)))+
geom_boxplot() + geom_point()+ylim(-2, 1)+
labs(title = "Surface Charcoal", x = "Number of cycles. Time frozen", y="Regularity") +
theme_minimal()+
theme(legend.position = "bottom")
ccov160F<-ggplot(DataTime160FBA,aes(interaction(Nb_Cy,
Time_frozen),log10(cofvariation),colour = interaction(Nb_Cy, Time_frozen)))+
geom_boxplot() + geom_point()+ylim(-2, 1)+
labs(title = "Buried Ash", x = "Number of cycles. Time frozen", y="Regularity") +
theme_minimal()+
theme(legend.position = "bottom")
dcov160F<-ggplot(DataTime160FBC,aes(interaction(Nb_Cy,
Time_frozen),log10(cofvariation),colour = interaction(Nb_Cy, Time_frozen)))+
geom_boxplot() + geom_point()+ylim(-2, 1)+
labs(title = "Buried Charcoal", x = "Number of cycles. Time frozen", y="Regularity") +
theme_minimal()+
theme(legend.position = "bottom")

figure4 <- ggarrange(acov160F, bcov160F, ccov160F, dcov160F,
                    ncol = 2, nrow = 2)
figure4

```

Appendix 5: Results for Statistical analysis

Table 13: Effect of number of cycles and moisture content on thickness and regularity

Average Thickness						Average thickness											
	Df	Mean Sq	F value	Pr(>F)	Sig	Surface Ash					Regularity						
						Df	Mean Sq	F value	Pr(>F)	Sig	Df	Mean Sq	F value	Pr(>F)	Sig		
Position:Layer:Water	3	10.79	9.983	2.04E-05	***	Water	1	2.174	2.62	0.12783	Water	1	0.6831	21.716	0.000368	***	
Position:Layer:Nb_Cy	3	3.75	3.472	0.02158	*	Nb_Cy	1	12.324	14.85	0.00176	**	Nb_Cy	1	0.7943	25.253	0.000186	***
Position:Water:Nb_Cy	2	5.83	5.392	0.00707	**	Water:Nb_Cy	1	3.926	4.731	0.04725	*	Water:Nb_Cy	1	0.2406	7.648	0.015174	*
Position	1	26.56	24.565	6.39E-06	***	Residuals	14	0.83				Residuals	14	0.0315			
Layer	1	121.49	112.379	2.76E-15	***	Surface Charcoal											
Water	1	0.42	0.388	0.53584			Df	Mean Sq	value	Pr(>F)	Sig	Df	Mean Sq	F value	Pr(>F)	Sig	
Nb_Cy	1	1.45	1.34	0.25173		Water	1	12.641	8.281	0.0122	*	Water	1	0.00074	0.009	0.927	
Residuals	59	1.08				Nb_Cy	1	0.08	0.053	0.822		Nb_Cy	1	0.07887	0.937	0.349	
Regularity						Water:Nb_Cy	1	3.894	2.551	0.1325		Water:Nb_Cy	1	0.00164	0.019	0.891	
	Df	Mean Sq	F value	Pr(>F)		Residuals	14	1.527				Residuals	14	0.08416			
Position:Layer:Water	3	0.27775	6.532	0.000699	***	Buried Ash											
Position:Layer:Nb_Cy	3	0.20744	4.879	0.004302	**		Df	Mean Sq	F value	Pr(>F)	Sig	Df	Mean Sq	F value	Pr(>F)	Sig	
Position:Water:Nb_Cy	2	0.14138	3.325	0.042951	*	Water	1	0.2139	0.197	0.664		Water	1	0.2139	0.197	0.664	
Layer:Water:Nb_Cy	1	0.09215	2.167	0.146398		Nb_Cy	1	0.0158	0.015	0.906		Nb_Cy	1	0.0158	0.015	0.906	
Position	1	0.22604	5.316	0.024726	*	Water:Nb_Cy	1	0.0356	0.033	0.859		Water:Nb_Cy	1	0.0356	0.033	0.859	
Layer	1	0.3097	7.284	0.009101	**	Residuals	14	1.087				Residuals	14	1.087			
Water	1	0.12715	2.99	0.089078	.	Buried Charcoal											
Nb_Cy	1	0.27196	6.396	0.014179	*		Df	Mean Sq	F value	Pr(>F)	Sig	Df	Mean Sq	F value	Pr(>F)	Sig	
Residuals	58	0.04252				Water	1	1.558	1.802	0.2008		Water	1	0.04997	1.538	0.235	
						Nb_Cy	1	0.895	1.035	0.3261		Nb_Cy	1	0.00009	0.003	0.958	
						Water:Nb_Cy	1	6.666	7.711	0.0148	*	Water:Nb_Cy	1	0.03525	1.085	0.315	
						Residuals	14	0.864				Residuals	14	0.03249			

cycles(0,60) *water

Table 14: Effect of the number of cycles

Average Thickness					
	Df	Mean Sq	F value	Pr(>F)	Sig
Layer:Position: Nb_Cy	1	5.78	6.476	0.013355	*
Layer:Position	1	12.9	14.449	0.000324	***
Layer:Nb_Cy	1	1.26	1.409	0.23964	
Position:Nb_Cy	1	5.08	5.689	0.020044	*
Layer	1	88.03	98.576	1.40E-14	***
Position	1	51.82	58.032	1.52E-10	***
Nb_Cy	1	10.43	11.68	0.001103	**
Residuals	64	0.89			
Regularity					
	Df	Mean Sq	F value	Pr(>F)	Sig
Position:Nb_Cy	1	0.2212	4.832	0.031399	*
Position	1	0.1823	3.983	0.050041	.
Nb_Cy	1	0.6223	13.593	0.000457	***
Layer	1	0.9971	21.781	1.51E-05	***
Residuals	67	0.0458			

Cycles 0,1,10,30,60

Surface Ash Correlation test		
S =	1496.1,	p-value = 0.01963
alternative hypothesis: true rho is not equal to 0		
sample estimate of	rho	-0.54392
Surface Charcoal Correlation test		
S =	1187.8,	p-value = 0.3675
alternative hypothesis: true rho is not equal to 0		
sample estimate of	rho	-0.22584
Buried Ash Correlation test		
S =	879.62,	p-value = 0.7158
alternative hypothesis: true rho is not equal to 0		
sample estimate of	rho	0.092244
Buried Charcoal Correlation test		
S =	1237.2,	p-value = 0.2663
alternative hypothesis: true rho is not equal to 0		
sample estimate of	rho	-0.27673

Appendix 6: Micromorphology Supporting Information

After 60 Cycles

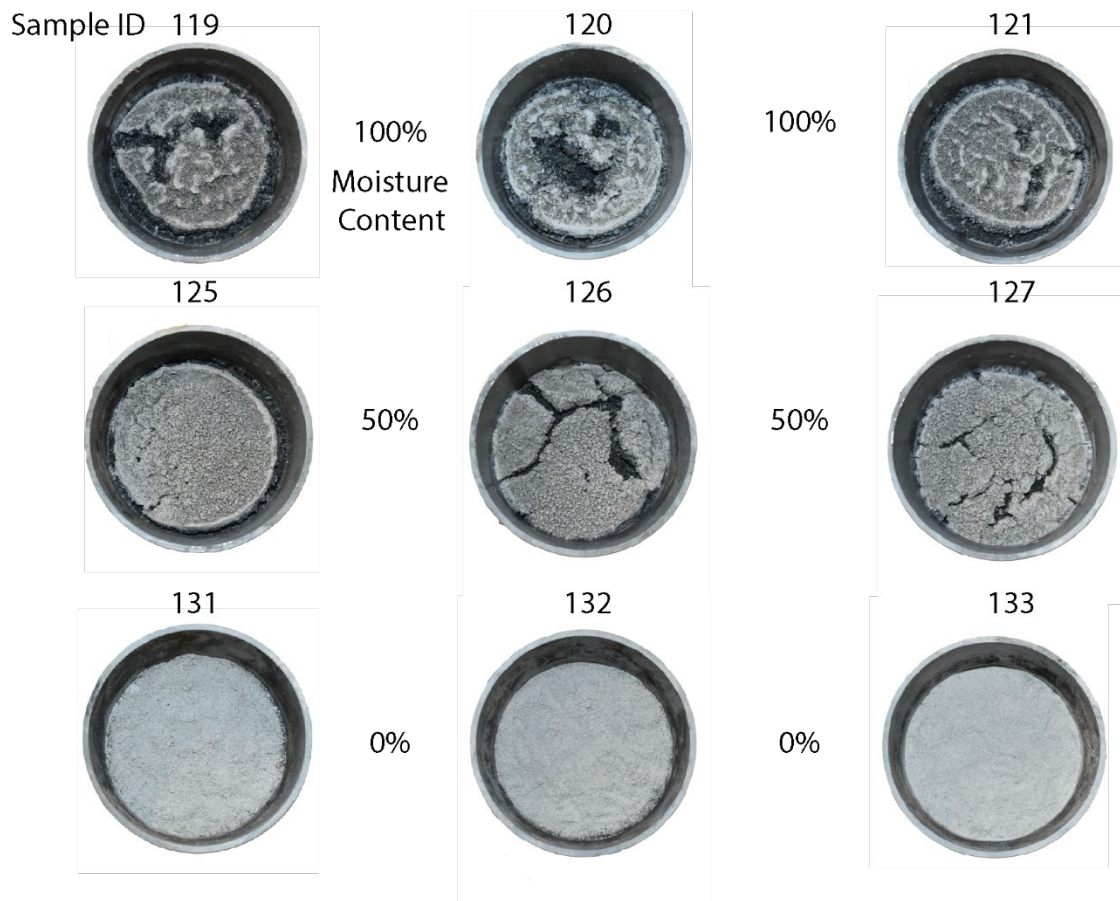
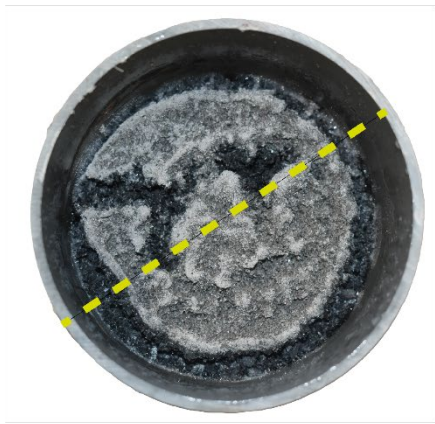


Figure 54: Top view of 100% (samples 119 – 121), 50% (125-127), and dry (131-133) after 60 cycles.



Top View



Bisected View



Thin Section

Sample: 119 -Surface - 100% Moisture content - 60 cycles

Figure 55: Top view, bisected view, and thin section of sample 119 after 60 cycles. The yellow dashed lines indicates where the sample was bisected