Forthcoming Current Anthropology Wenner-Gren Symposium
Supplementary Issues (in order of appearance)

Human Colonization of Asia in the Late Pleistocene. Christopher J. Bae, Katerina Douka, and Michael J. Petraglia, eds.
The Anthropology of Corruption. Sarah Muir and Akhil Gupta, eds.
Cultures of Militarism. Catherine Besteman and Hugh Gusterson, eds.

Previously Published Supplementary Issues

Working Memory: Beyond Language and Symbolism. Thomas Wynn and Frederick L. Coolidge, eds.
Engaged Anthropology: Diversity and Dilemmas. Setha M. Low and Sally Engle Merry, eds.
The Biological Anthropology of Living Human Populations: World Histories, National Styles, and International Networks. Susan Lindee and Ricardo Ventura Santos, eds.
Alternative Pathways to Complexity: Evolutionary Trajectories in the Middle Paleolithic and Middle Stone Age. Steven L. Kuhn and Erella Hovers, eds.
Crisis, Value, and Hope: Rethinking the Economy. Susana Narotzky and Niko Besnier, eds.
The Life and Death of the Secret. Lenore Manderson, Mark Davis, and Chip Colwell, eds.
Reintegrating Anthropology: From Inside Out. Agustín Fuentes and Polly Wiessner, eds.
New Media, New Publics? Charles Hirschkind, María José A. de Abreu, and Carlo Caduff, eds.

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Fire and the Genus *Homo*

*Leslie C. Aiello*
Fire and the Genus *Homo*
Wenner-Gren Symposium Supplement 16

*Dennis M. Sandgathe and Francesco Berna*
Fire and the Genus *Homo*
An Introduction to Supplement 16

*Paul Goldberg, Christopher E. Miller, and Susan M. Mentzer*
Recognizing Fire in the Paleolithic Archaeological Record

*Vera Aldeias*
Experimental Approaches to Archaeological Fire Features and Their Behavioral Relevance

*J. A. J. Gowlett, J. S. Brink, Adam Caris, Sally Hoare, and S. M. Rucina*
Evidence of Burning from Bushfires in Southern and East Africa and Its Relevance to Hominin Evolution

*Carolina Mallol and Auréade Henry*
Ethnoarchaeology of Paleolithic Fire: Methodological Considerations

*Simon J. Holdaway, Benjamin Davies, and Patricia C. Fanning*
Aboriginal Use of Fire in a Landscape Context: Investigating Presence and Absence of Heat-Retainer Hearths in Western New South Wales, Australia

*Sarah Hlubik, Francesco Berna, Craig Feibel, David Braun, and John W. K. Harris*
Researching the Nature of Fire at 1.5 Mya on the Site of Fxj20 AB, Koobi Fora, Kenya, Using High-Resolution Spatial Analysis and FTIR Spectrometry

*Nira Alperson-Afil*
Spatial Analysis of Fire: Archaeological Approach to Recognizing Early Fire

http://www.journals.uchicago.edu/CA
Xing Gao, Shuangquan Zhang, Yue Zhang, and Fuyou Chen
Evidence of Hominin Use and Maintenance of Fire at Zhoukoudian S267

Harold L. Dibble, Aylar Abodolahzadeh, Vera Aldeias, Paul Goldberg, Shannon P. McPherron, and Dennis M. Sandgathe
How Did Hominins Adapt to Ice Age Europe without Fire? S278

Randall White, Romain Mensan, Amy E. Clark, Elise Tartar, Laurent Marquer, Raphaëlle Bourrillon, Paul Goldberg, Laurent Chiotti, Catherine Cretin, William Rendu, Anne Pike-Tay, and Sarah Ranlett
Technologies for the Control of Heat and Light in the Vézère Valley Aurignacian S288

Richard Wrangham
Control of Fire in the Paleolithic: Evaluating the Cooking Hypothesis S303

Ran Barkai, Jordi Rosell, Ruth Blasco, and Avi Gopher
Fire for a Reason: Barbecue at Middle Pleistocene Qesem Cave, Israel S314

Amanda G. Henry
Neanderthal Cooking and the Costs of Fire S329

Jill D. Pruetz and Nicole M. Herzog
Savanna Chimpanzees at Fongoli, Senegal, Navigate a Fire Landscape S337

Michael Chazan
Toward a Long Prehistory of Fire S351

Dennis M. Sandgathe
Identifying and Describing Pattern and Process in the Evolution of Hominin Use of Fire S360
Fire and the Genus *Homo*

Wenner-Gren Symposium Supplement 16

Leslie C. Aiello

“Fire and the Genus *Homo*” was the 152nd symposium in the Wenner-Gren series and the sixteenth open-access supplement of the Foundation’s journal, *Current Anthropology*. The symposium was organized by Dennis M. Sandgathe and Francesco Berna (Simon Fraser University) and was held October 16–22, 2015, at Tivoli Palácio de Seteais in Sintra, Portugal (fig. 1). Wenner-Gren symposia are a long-standing tradition of the Foundation, having been initiated in 1958 at the Foundation’s European conference center, Burg Wartenstein castle, Austria. Many of the edited volumes resulting from those meetings became landmark contributions to the discipline. However, over the years, as the field grew in both size and diversity and opportunities for publication increased, edited volumes lost much of their earlier cachet. In 2010 we introduced the open-access supplementary issues of *Current Anthropology* specifically to raise the visibility of Wenner-Gren symposia. By the end of 2016 our symposium supplementary issues had been accessed a total of 900,000 times with an average of 70,000 accesses per issue. We could not be happier with this success.

"Fire and the Genus *Homo*" follows in our tradition of supporting symposia on big-issue topics. In their introduction, Sandgathe and Berna, the guest editors, express surprise that Wenner-Gren has not sponsored prior symposia on fire. From the Foundation’s point of view, this is not surprising. As Sandgathe and Berna (2017) say, until recently fire was both understudied and considered by many to be without problem or major interest.

The Foundation has, however, sponsored many meetings on human evolution and human adaptation. In the early years there were a number of meetings that focused primarily on the then-emerging East African fossil evidence for human evolution (e.g., Bishop and Clark 1967; Butzer and Isaac 1975; Coppen et al. 1976; Washburn 1964). Subsequent symposia have emphasized both the evolution of human adaptation and the empirical basis for inference. For example, Gibson and Ingold (1993) addressed the relationship between tools, language, and cognition in human evolution, Enfield and Levinson (2006) examined the roots of human sociality, and Wynn and Coolidge (2010) looked at the working memory in relation to the evolution of the brain, language, and symbolism. Antón and Aiello (2012) addressed the evolution of adaptation in the genus *Homo*, drawing on evidence from both the fossil record and human biology, and Kuhn and Hovers (2013) explored human evolutionary trajectories in the Middle Paleolithic and the Middle Stone Age. There is also a forthcoming issue on the human colonization of Asia in the Late Pleistocene (Baë, Douka, and Pettaglia, forthcoming).

Sandgathe and Berna (2017) provide many reasons to focus on fire at this particular point in time. There has been an impressive upsurge in research into the evolution of human fire usage over the past decade. In addition, some firmly embedded preconceptions and popular theoretical models (e.g., the cooking hypothesis) generate considerable debate and discussion. For example, Sandgathe and Berna point out that although many researchers believe that by the Middle Paleolithic, if not earlier, hominins regularly made and used fire, there is no robust evidence to support this before the appearance of anatomically modern humans (see also Dibble et al. 2017; but see Henry 2017). This leaves considerable controversy over the significance of evidence for fire (or lack thereof) in the earlier hominin sites in Africa, the Near East, and Europe. The debate surrounding the significance of cooking to human adaptation and brain evolution by approximately 1.5 million years ago is part of this discussion (Wrangham 2017). Why is the evidence for fire usage at this stage so sparse and ambiguous when it would appear to be fundamentally important to the evolution of *Homo*?

"Fire and the Genus *Homo*" addresses these issues and many more. It provides the most current and up-to-date summary and discussion of the evidence for and debates surrounding the human use of fire. For this reason alone it will be a go-to reference for anyone interested in fire and its importance to human evolution. Sandgathe and Berna (2017) conclude by calling for more collaborative work on the evolution of human use of fire and for new analytical methods and skills to confidently interpret the archaeological record. There are still many unanswered questions to be addressed, but no one can doubt the importance of fire to humans. Sometimes the most obvious aspects of life are those that are taken for granted and receive the least scientific attention. It is exciting to see the growing anthropological interest in fire and to speculate on how many of our current preconceptions will be overturned by future evidence. This is exciting research and certainly a big issue in the modern discipline.

Wenner-Gren symposia are partnerships between the Foundation and the academic organizers, and we are always looking...
for new and important ideas from all branches of anthropology for future symposia and eventual CA publication. Please contact us with your proposals. Information about the Wenner-Gren Foundation, the symposium program, and what constitutes a good symposium topic can be found on the Foundation’s website (http://www.wennergren.org/programs/international-symposia).

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Fire and the Genus *Homo*

An Introduction to Supplement 16

by Dennis M. Sandgathe and Francesco Berna

Employing fire as an adaptive aid represents one of the most important technological developments in the course of hominin evolution, and, not surprisingly, research into the prehistoric use of fire has a long history. Over the last decade or so there has been a notable increase in research. Some people have continued to focus on better understanding of the timing of the beginning of fire use, but some have also been trying to understand something of its role in the evolution of the genus *Homo*. In the fall of 2015 a symposium was held in Portugal that brought together 17 researchers who have contributed significantly in recent years to this subject. These contributions include improving the type and quality of archaeological and ethnoarchaeological data, collecting and interpreting fire residue data from archaeological sites from various time periods and regions, and developing models of fire as an ecological resource and the role of cooking in hominin evolution. A result of the symposium was the recognition of the need to focus less on data from individual sites and more on the broader role of fire in hominin adaptations and to concentrate more on developing the analytical methods and skills to confidently interpret what we see in the archaeological record.

While it may be difficult to identify major events in the evolution of human physiology, we can certainly identify important cultural ones, such as the initial use of stone tools, the development of artificial shelter, or the beginning of food production. Of course, researchers may debate which developments are the most significant, but when it comes to major technological developments over the course of the evolution of the genus *Homo*, almost all would certainly include the use of fire. It is difficult to overemphasize the significance of this development. In whatever manner fire was initially acquired, whatever it was initially used for, whatever its function at various times and places over the course of subsequent prehistory, and however the hominin-fire relationship developed over time, its far-reaching potential is clear. It allowed us to significantly modify our environment and its resources, to survive in extremely cold environments, and to keep dangerous animals at bay. With fire we can see better in the dark, thus effectively extending the period in each day for activities; we can modify raw materials to expand the range of our material culture, and we can cook our food in order to make it easier and safer to consume and at the same time significantly increase its caloric returns. Beyond significantly increasing our adaptive range and potential, the use of fire very likely played a major role in subsequent physiological changes such as our decrease in gut size and increase in encephalization. The papers in this volume, originally presented at a workshop titled “Fire and the Genus *Homo*,” bring together a wide range of current perspectives and data on this important topic.

Early Research

The recognition of the importance of fire in hominin adaptations can be traced back to very early in the history of prehistoric archaeology and human evolution research (e.g., Darwin 1871). Since then questions about early fire use have been evolving, but rather slowly. For much of the earlier history of research, interest was focused heavily on simply determining when and where fire was first used (e.g., Black 1932; Hough 1926; Oakley 1955, 1956). Moreover, much of this research was not necessarily hampered by any concern about the authenticity of potential evidence for fire use at early sites (e.g., Black 1932; Stewart 1956), and there was also a strong presumption that once fire use was “discovered,” it subsequently became a universal and ubiquitous component of all hominin populations (e.g., Oakley 1955, 1956; Stewart 1956). Likewise in the early years there was little specific interest in how fire use came to be incorporated into the hominin technological repertoire: it was simply the result of a discovery. And there was also limited interest in exploring what early fire might have been used for, other than general suggestions related to cooking food, providing heat, or scaring off dangerous animals (e.g., Oakley 1955). A

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significant exception to much of this early history is the work of Kenneth Oakley. In the 1950s he published important articles on the (at that point very limited) evidence for Paleolithic use of fire. This included discussions of the nature of this evidence and potential problems with some of it (including the potential for natural fire residues to be mistaken for anthropogenic ones; Oakley 1954, 1955, 1956, 1961). However, there were no real discussions about the “development” of fire use—that is, as a process rather than an event—and there was no discussion about the interaction between fire use and hominin physiological evolution.

In the early decades of Paleolithic research there were limited field methods available for the accurate identification and interpretation of sediments that could represent potential evidence of hominin fire use. At a number of sites this led to the misidentification of the presence of fire based on sediments that were in fact unrelated to burning (Goldberg, Miller, and Mentzer 2017). For example, at the site of Fontchevade in southwestern France patches of manganese dioxide were mistaken for charcoal (Chase et al. 2009), and at Zhoukoudian, China (Goldberg et al. 2001; Weiner et al. 1998), lenses of organic matter and layers of very fine silts from Middle Pleistocene contexts were mistaken for charcoal and ash. A similar mistaken interpretation occurred at South Africa’s Cave of Hearths (Oakley 1957), and more recently there is the example of Schöningen in northern Germany (Stahl Schmidt et al. 2015). There was also a serious lack of detail in the descriptions of real or potential fire residues in early sites. For example, the term “hearth” was often used rather indiscriminately to refer to what were simply dark or reddish patches in the sediments or a scattering of a few burned bones, charcoal, or burned lithics, and such evidence was rarely quantified (e.g., Bader and Klein 1965; Breuil 1922; de Lumley and Bard 1972; Garrod 1951; Henri-Martin 1965; Klein 1965; Oakley 1954, 1956, 1961; Stewart 1956; Waechter 1951). This meant that other researchers could not properly assess such findings in terms of how accurately they reflected evidence for fire use in the archaeological record. So the recovery of minute traces of what was assumed to be ash or charcoal resulted, in many cases, in those sites being put forward as examples of the frequent use of fire. Over time, such lack of rigor resulted in an overestimation of the frequency of fire residues in Paleolithic sites and, in turn, how common fire use likely had been throughout the Paleolithic (e.g., Roebroeks and Villa 2011; Sandgathe et al. 2011b; Stahl Schmidt et al. 2015).

However, while the evidence for fire use from Lower and Middle Pleistocene contexts was limited and subject to debate (Barbetti 1986; Bellomo 1993, 1994; Gowlett 2006; James 1989), unmistakable examples of hominin use of fire, including well-preserved combustion features, had been recognized in Late Pleistocene contexts. This was especially the case with sites associated with Neanderthals in Western Eurasia (e.g., Oakley 1956). Fire residues, however variously described, occurred frequently enough in these contexts that, taken at face value, they seemed to indicate that at least by this point in prehistory fire use had become common. In fact, the literature would suggest that currently the majority of researchers believe that by the Middle Paleolithic, if not earlier, hominins were regularly using fire and had developed the technology to create it at will; conversely, in contexts where evidence for fire was lacking, the absence was interpreted simply as being a product of taphonomic processes. However, there was no evidence of any hominin-fire interaction predating the emergence of the genus Homo. This continues to be the case today: regardless of the specific timing for when fire came to be used, it is clearly a behavior associated exclusively with species of Homo and does not appear to predate the emergence of Homo ergaster. We should note, however, that the recognition of a certain degree of passive interaction between chimpanzees and fire (Pruetz and Herzog 2017; Pruett and LaDuke 2010) as well as some species of monkeys (Herzog et al. 2014) suggests the possibility of similar behaviors extending back into the Pliocene.

Research in Recent Years

While there has long been a general interest in the question of Paleolithic fire use, the last couple of decades—and especially the last several years—have seen a particularly strong uptick in research on this topic. Since 2000 there has been a three- to fourfold increase in the number of journal publications specifically on Paleolithic fire use. This upsurge is the product of a number of factors that include important new discoveries of fire residues associated with various Homo species in Africa, southwest Asia, and Europe, the influence of the cooking hypothesis (Alperson-Afil and Goren-Inbar 2006; Alperson-Afil, Richter, and Goren-Inbar 2007; Berna et al. 2012; Goren-Inbar et al. 2004; Gowlett and Wrangham 2013; Karkanas et al. 2007; Preece et al. 2006; Schieg1 et al. 1996; Wrangham 2009), and the development of new methods associated with the recovery and interpretation of archaeological deposits (e.g., Goldberg, Miller, and Mentzer 2017; Mentzer 2014). The latter development has put us in a much better position to distinguish actual fire residues and features from deposits that can potentially mimic them (Bellomo 1994; Berna and Goldberg 2008). A small number of researchers have also begun to broaden our understanding of the nature of natural fires, their resulting residues, and their potential effect on archaeological remains (Barbetti et al. 1980; Gowlett et al. 1981, 2017). These two developments have resulted in a more generally critical approach to claims for fire, especially in particularly old contexts (James 1989; Roebroeks and Villa 2011; Sandgathe et al. 2011b).

New approaches are now being used that allow us to test the effects of taphonomy on the presence or absence of ephemeral fire residues in site components. Direct fire residues like charcoal, ash, and heat-altered sediments are easily eroded or dissolved by a range of taphonomic processes, and while we recognize that the absence of these residues cannot be taken as evidence for a lack of fire use at a site, neither can we build models or construct hypotheses about prehistoric fire use on
contentions that fire could have been used in contexts where there is no positive evidence for it. However, some fire residues such as fat-derived char (e.g., Goldberg et al. 2009; Mallol et al. 2013) and burned lithics (and to a lesser extent burned bones) are far less affected by common taphonomic processes. Several research projects have been investigating how informative these residues are about the apparent frequency of fire use at Paleolithic sites (Aldeias et al. 2012; Dibble et al. 2009, 2017; Goldberg et al. 2012; Sandgathe et al. 2011a; Shimelmitz et al. 2014). Others have been looking at spatial patterning in burned lithics (e.g., Alperson-Afil, Richter, and Goren-Inbar 2007; Gowlett 2006), often with the implicit goal to identify criteria by which the results of natural fire can be distinguished from results of anthropogenic fire (e.g., Gowlett et al. 2017; Hlubik et al. 2017). As a result of improvements in the types and quality of data and an increased appreciation for the importance of biocultural evolution, there are some clear and significant shifts from previous decades in how most researchers view the probable complexity of hominin interaction with and use of fire. This change has resulted in changes in the way Paleolithic fire use should be studied and in what constitutes evidence for various fire-related behaviors.

The Symposium “Fire and the Genus Homo”

When we first proposed to Leslie Aiello and Laurie Obbink at the Wenner-Gren Foundation that they devote one of their two annual symposia to early fire use, we were quite surprised to find that over the Wenner-Gren symposium history that spans almost 60 years (and over 150 conferences!), this topic had never been covered before. This is unexpected considering how much interest archaeologists and anthropologists have always shown in the subject of early hominin fire use. However, considering the increased emphasis on research on this topic over the last several years, this did seem like a particularly opportune time to finally bring together a significant number of the scholars currently leading research into this area of hominin behavior and adaptation. We only regret not being able to include all those researchers who are currently doing research on Paleolithic fire or who have made major contributions to this topic in the past.

It is becoming increasingly clear that we are now at the point where we can begin developing a more evolutionary approach to the role of fire in hominin (or homininae?!) adaptations, and this symposium was intended to instigate and facilitate discussion and collaboration along those lines. During the discussions in this symposium it became clear that the field needs to move on from treating hominins establishing “control” of fire as a one-time event at some distant time in the ancient past, from debating the timing of this, and from assuming that from that point on, fire was a regular component of all hominins’ adaptations. Obviously, we still need to establish an understanding of the timing of the process of hominin development of fire use, and so it is still very important that we identify examples in the archaeological record of early hominin interaction with fire. These are still our primary sources of data. However, we are coming to recognize that the relationship between hominins and fire was likely a long and complex one, possibly following many varied stages of development. Perhaps not at first, but as this relationship became more entangled, fire came to play ever more important roles in hominin adaptations, and eventually the multifaceted use of fire became a necessity for the survival of modern humans: we became obligate fire users.

The Organization of This Volume

This volume follows the general organization of the symposium on which it is based. The topic “Fire and the Genus Homo” includes a wide range of distinct but overlapping areas of research, and we have tried to organize the participants’ contributions in this manner.

Prehistoric Fire Use: The Data

Regardless of the varied approaches that researchers take to understand the nature of Paleolithic interaction with fire, all interpretation ultimately rests on the nature and quality of our most basic types of data—residues and alterations directly resulting from fire—and researchers have been expanding the types of data that can be brought to bear on our questions. We rely on these data to provide the most basic contexts for our subsequent interpretations: Are sediments in a site actually fire residues? Are these fire residues the result of natural or anthropogenic fire? What type of fuel was used? What temperature did the fire reach? But we are now trying to expand our questions to include investigations into the structure and function of fires, the latter being the most difficult aspect to demonstrate. These questions lead us to consider even more carefully what types of data should be recorded, what types of samples should be taken, and what analyses should be carried out as a normal course of excavation in sites with potential evidence of early hominin interaction with fire. Building on the work of Barbetti (1986), Goldberg, Miller, and Mentzer (2017) formalize three basic questions that should comprise the identification and interpretation of early Homo fire use: (1) Are the sediments or objects in question actually burned? (2) If they are burned, what was the nature and context of their deposition? (3) Were they burned by hominins? Currently there is a range of data, analytical techniques, and methodologies that are necessary in trying to answer these questions, and many of these should be considered as minimal standards in the recovery and interpretation of potential evidence of early fire use. Goldberg, Miller, and Mentzer (2017) and Aldeias (2017) summarize the types of data and analyses as well as quantification that can differentiate actual burned residues from sediments that can mimic these. Ultimately, the most effective approach is going to be the integration of high-resolution spatial analysis of the archaeological record and
microscopic and chemical-physical characterization of the archaeological deposits (microcontextual approach).

However, our understanding of the relationship between prehistoric fire and the resulting archaeological residues depends heavily on an understanding of the interaction between fire and its immediate environment and the residues and alterations that result from this interaction. This understanding relies very heavily on experimental work (e.g., Aldeias et al. 2016; Bellomo 1993; Berna et al. 2007; Gowlett et al. 2017; Mallol and Henry 2017; Mallol et al. 2007, 2013; March 1992; March et al. 2014; Théry-Parisot 2001; Théry-Parisot and Costamagno 2005). Having an understanding of what residues and alterations of the immediate environment occur under different heat conditions (e.g., the size of the fire, the duration of the fire, what fuel was used, the nature of the substrates upon which the fire was constructed) and under what conditions these residues and alterations can survive in the archaeological record is essential for the further development of methods that can address the three questions laid out by Goldberg, Miller, and Mentzer (2017).

A second source of information about fire in the archaeological context comes from the ethnographic record. We have come to recognize the problems inherent with trying to apply ethnographic data or models wholesale to prehistoric contexts, especially when we are dealing with premodern hominin species. There is no a priori reason to expect exactly the same interactions with the environment and the exact same limits on the range of behaviors between modern humans and extinct species of Homo. Indeed ethnographic analogy should not be completely trusted as compelling evidence in prehistory (Wylie 1985). However, we also recognize that ethnographic data can be a powerful source of insight into the potential types and ranges of evidence left behind by behaviors and technologies that hominins may have adopted under certain environmental circumstances (David and Kramer 2001). The ethnoarchaeology of fire use among living small-scale societies provides a wealth of comparative materials for the interpretation of archaeological fire remains. Such studies can provide important insights into how fire creation technologies, fire function, fire structures, the repeated use and duration of use of a single fire, and fires using different fuels are transformed when they enter the archaeological record (Mallol and Henry 2017; Mallol et al. 2007). In this volume, ethnoarchaeological investigations of fire use among two different small-scale society groups—a group of Hadza foragers in Tanzania and Evenk reindeer herders and hunters of southeastern Siberia—included residue analysis of combustion remains (Mallol and Henry 2017). As with other experimental approaches, these types of studies provide data against which archaeological observations can be compared. For example, how do different types of fuels behave in different combustion settings, and what sort of fire functions can they be linked to? Geoarchaeological analysis of ethnographic fire use provides major insights into taphonomy and formation processes: what is the nature of the residues left behind, if any; what sort of alterations occur to substrates with different types of combustion features and different fuel types; and under what conditions will combustion residues be preserved?

Goldberg, Miller, and Mentzer’s (2017) third question (whether or not the evidence of burning is a product of hominins) is especially important in many Paleolithic contexts, especially the open-air sites, because fire residues may be a product of natural fires with no relationship to hominin behavior. In many ecosystems, especially in warmer midlatitudes and forested regions, natural fires are very common, which means that for many archaeological sites natural fires are an equally plausible source for fire residues and alterations of sediments, bones, and lithics (for a particular example, see the prelude in Goldberg, Miller, and Mentzer 2017). It has become apparent that we need a much better understanding of the frequency, variability, effects on substrates, and resulting products of natural fire across a range of different environments so that we can begin to distinguish these from the products of anthropogenic fires—in essence, control for the natural fire “background noise” across the landscape. Based on observations and experiments with natural and controlled-burn fires in eastern and southern Africa, Gowlett et al. (2017) call into question some previous assumptions held about the differences between natural fires and anthropogenic ones. For example, they observed that in natural grass fires temperatures can reach up to and beyond the limit typically ascribed to campfires. However, the nature of residues and alterations produced by a fire depend heavily on the duration of the fire and the temperatures reached. There is significant variability in these variables across different types of wildfires and even within individual wildfires, depending on the nature, concentration, and density of the vegetation.

Lower and Middle Pleistocene Use of Fire

It is in African Lower Pleistocene contexts where we get the earliest potential evidence for hominin-fire interaction, and for many researchers this indicates that Homo ergaster/Homo erectus could have been regularly using fire well before a million years ago (e.g., Alperson-Afil 2017; Bellomo 1994; Brain and Sillen 1988; Clark and Harris 1985; Gowlett and Wrangham 2013; Shimelmitz et al. 2014). However, the number of examples of Lower Pleistocene fire residues associated with hominin sites is very small when compared with the totality of coeval sites, and the evidence (patches of rubefied sediments that may indicate hearth locations, isolated burned bones, and isolated or small concentrations of burned lithics) is unconvincing to many (Chazan 2017; Roebroeks and Villa 2011). As discussed above, many researchers recognize that given the frequencies of natural fires in Africa today, especially in Savannah and Sahel ecosystems, there is a reasonable possibility that such fire residues in archaeological sites are not the products of hominin behavior (e.g., Gowlett et al. 2017; Hlubik et al. 2017; Roebroeks and Villa 2011; Sandgathe et al. 2011b). Over the hundreds of thousands of years that these sites lay on the
landscape, natural fires must have passed over them many times. For archaeological sites that are not deeply buried, the chances are not insignificant that the later fires could affect artifacts, bones, and sediments (Buenger 2003). In the case of a burning tree or shrub, the result can be a concentration of burned sediments, bones, or lithics that could mimic the remains of a hearth (Bellomo 1994; Gowlett et al. 2017). This means that simply measuring (through methods like magnetic susceptibility and thermoluminescence) the temperatures that altered sediments or heated flints or performing simple spatial analysis of these residues are not enough to distinguish natural from anthropogenic fires. However, we might be able to get at this problem through the careful analysis of patterning in the burning in these early archaeological sites. This is the approach that Hlubik et al. have been taking in their study of burned basalt, bone, and soil aggregates at the site of Fxj20AB at Koobi Fora in Kenya. They attempt to identify patterning in the distribution of burned artifacts that cannot be explained as a result of the passage of natural fires through or over the site and that indicate that the fire and the occupation of the site co-occurred. This would certainly make it much more likely that the hominins were interacting with and perhaps responsible for the fire.

Researchers have identified sites dated to the end of the Lower Pleistocene with potential evidence for hominin interaction with fire. One of these is Wonderwerk Cave in South Africa, which has yielded ash and burned bone fragments deep inside the cave in deposits dated to a million years ago (Berná et al. 2012; Chazan 2017). It is difficult to propose natural fires as a source for these residues as there is no evidence that any of the sediments washed into the cave and it seems very unlikely that natural fire could occur so deeply inside the cave. There are also sites of similar age outside of Africa. Gesher Benot Ya’akov in Israel, where a number of concentrations of burned lithics across the site strongly suggest the locations of hearths dated to approximately 800 kya (Alperson-Afil 2017; Alperson-Afil, Richter, and Goren-Inbar 2007) and Cueva Negra in Spain where, like Wonderwerk Cave, fire residues occur inside a cave (Walker et al. 2016).

The record of fire in archaeological sites changes dramatically in the Middle Pleistocene, with a large increase in the number of sites and site components with fire residues and undeniable examples of hominin use of fire. This includes intact hearths in several sites in Israel—Qesem Cave (Barkai et al. 2017; Karkanas et al. 2007), Hayonim Cave (Goldberg and Bar-Yosef 2002), and Tabun Cave (Schimmelzelt et al. 2014)—and hearth structures identified during recent excavations in layer 4 of Zoukoudian in China (Gao et al. 2017). Whereas we have no idea how fire was being obtained, it is clear that the hominins occupying these sites were using fire and often used it repeatedly, in the same locations within the sites (e.g., at Qesem Cave; Shahack-Gross et al. 2014). These sites dating to 300–400 kya are the earliest evidence so far for fire beginning to take on a more important role in *Homo* adaptations. It is very difficult to get a realistic idea of the actual nature of this interaction or the role that fire was playing. To get at this we need more information about, among other things, the actual frequency of use of fire at these sites. Was fire being used every time a group occupied a site? Or was its use intermittent, and if so, how much time passed between uses, and why was it just used at some sites and not others? It would be important to have some understanding of how regular fire use was, how integrated it had become in hominin adaptations, and what function or functions it served before we are able to construct models about the role fire played and its potential impact on hominin biocultural adaptations at this point in prehistory.

**Fire Use in Late Pleistocene Europe and Holocene Australia**

The current evidence from several Spanish sites in the Atapuerca Hills and Orce Basin indicates that some species of *Homo* (some version of *H. erectus*) moved into Europe some time prior to 1.25 Mya (Carbonell et al. 2008; Moyano et al. 2011). However, evidence for any interaction with fire in any European sites older than around 400 kya is almost nonexistent (the one exception, so far, being Cueva Negra in Spain, which has fire residues that date to around 800 kya; Walker et al. 2016). While Lower and Middle Pleistocene occupations of Europe may have correlated strongly with warm climatic periods and warmer Mediterranean latitudes, it is still surprising that these African-adapted hominins were able to colonize European latitudes without the regular use of fire. However, that fire was not a requisite technology for hominins to do this was recognized many years ago (e.g., Perles 1981). By the end of the Middle Pleistocene, the majority of Eurasian site components still have little or no evidence for fire, but some do, and by the start of the Late Pleistocene a significant number do have very good evidence that Neanderthals regularly used fire (Roebroeks and Villa 2011). Because of this, for several decades now it appears that the general consensus is that regardless of what was going on in previous time periods and with other hominins, Neanderthals were creating and using fire at will and that it was an integral component of their adaptation (e.g., Barkai et al. 2017; Daniau, d’Errico, and Goñi 2010; Gowlett 2016; Pettitt 1997; Rolland 2004). In fact, it is difficult to imagine that even an apparently physiologically cold-adapted species like Neanderthals could survive the extreme colds of Ice Age Eurasia without fire. However, Dibble et al. (2017) present evidence from several French Middle Paleolithic sites that appears to support the idea that while Neanderthals were certainly using fire regularly during some periods, there are sites with evidence for major successive occupations spanning many thousands of years with no evidence that they were using fire over that period. The data from these sites seem to show a pattern of fire use that correlates counterintuitively with climate: Neanderthals were using fire during warm periods and apparently not during cold periods. Dibble et al. suggest a number of potential explanations for this that bring into question whether by the Late Pleistocene all hominins in all regions had the technology to make fire at will.
General perceptions among Paleolithic researchers appear to be that with the arrival of modern humans in Europe and throughout the subsequent Upper Paleolithic period, fire use was ubiquitous and had taken on an even more complex role in human adaptations (e.g., Chazan 2017; White et al. 2017). As presented by White et al., Upper Paleolithic sites in Europe contain a range of different fire structures, some with relatively complex stone arrangements (see also Movius 1966) that make it clear that many of these are not just general-use “hearth structures” providing heat for warmth and cooking. While the actual functions of these different structures has yet to be determined in most cases, their evidence strongly suggests a much wider range of applications of fire than anything observed in earlier periods. There is also a clear increase in the complexity of the spatial arrangement of occupation sites, with fire structures being major components of this organization.

However, the archaeological record is a product of taphonomic processes as much as—and often more than—the direct result of patterns of behavior (Holdaway, Fanning, and Shiner 2005). This is an important point when it comes to interpreting any aspects of the archaeological record but is especially pertinent when we are dealing with remains that are particularly susceptible to erosion and loss, as is the case with direct fire residues like charcoal and ash. Holdaway, Davies, and Fanning (2017) present an important example of this with Holocene age fire features in Australia. In the presented case, the preservation and visibility of any evidence of fire-related behavior is facilitated by the prehistoric use of stone structures as heat retainers. While the ephemeral residues like charcoal and ash generally disappeared very quickly, these structures survived more or less intact. One might then examine the temporal and spatial distribution of these features as direct sources of information about patterns of prehistoric use of fire. However, the analysis of Holdaway, Davies, and Fanning indicates that the frequency of these hearth structures in the archaeological record is also heavily influenced by taphonomic processes, particularly geomorphic development of landscapes. This serves as one cautionary tale (and a particularly powerful one considering the young age of these hearth structures) for any attempts to infer behavioral patterns directly from the presence or absence and frequency of any archaeological phenomena, not just fires.

Cooking

While fire has undoubtedly served a wide range of functions over the course of prehistory, a century of ethnographic observations from around the world has shown that cooking is universal among human groups. Thus it made sense to have a special section devoted to this.

People cook food for a variety of reasons, for example, making rotting meat safe to eat (e.g., Dibble et al. 2017) or denaturizing meat or plant food to make it easier to chew (e.g., Wrangham and Conklin-Brittain 2003; Zink and Lieberman 2016). For over a decade Wrangham (e.g., Wrangham 2007, 2009; Wrangham et al. 1999; Wrangham and Conklin-Brittain 2003) has made a compelling argument that modern humans need to cook our food in order to obtain the net energy returns required to support such a large brain while also having such a small gut and small teeth. Furthermore, he argues that this obligatory relationship between brain, gut, teeth, and cooking extends back to H. ergaster/H. erectus around or shortly after 2 Mya. Wrangham’s cooking hypothesis has come to be one of the more influential ideas in paleoanthropology today. However, the cooking hypothesis is arguing that cooking and fire use would have essentially been a daily activity over the last 2 Mya, while the current archaeological evidence for fire use over much of this time is sparse at best. Wrangham (2017) presents further arguments in support of the very early adoption of a cooked diet. He also addresses many of the potential problems the hypothesis faces and goes a long way toward reconciling some of the apparent inconsistencies between the hypothesis and the archaeological data.

Two other symposium contributions represent major data points along the prehistoric development of cooking. Barkai et al. (2017) discuss the significant fire residues at Qesem Cave, Israel, dated between 420 and 200 kya. They interpret these residues as the remains of meat-roasting fires that were used regularly and repeatedly, and they argue that this behavior was an essential component of hominin adaptations in the Levant in this period. What species of archaic Homo is represented at the sites is unclear, but presumably it is either Homo heidelbergensis or early Neanderthals.

Henry (2010) and Henry, Brooks, and Piperno (2011) have made significant contributions to our understanding of cooking and the role of plant foods in Neanderthal diets. Their analysis of phytoliths and starch grains incorporated into Neanderthal dental calculi strongly suggests that some plants were being integrated into their diet. The morphology of some starch grains in the calcui also suggests that some plants were being cooked before they were consumed (Henry 2015). However, much of the other evidence (stable isotope data and the faunal record) suggests that the Neanderthal diet was heavily meat focused (e.g., Richards and Trinkaus 2009) and that Neanderthals were not cooking their food at all times and in all places (e.g., Dibble et al. 2017; Sandgathe et al. 2011a, 2011b). Henry (2017) has taken a novel approach to understanding Neanderthal fire use patterns (although the implications are not restricted to any one species of Homo). She suggests that unlike recent modern human foraging societies, Neanderthals may have viewed fire as just another potentially exploitable resource among many available in the landscape. Whether or not they chose to exploit each resource depended on a cost-benefit approach, and this, of course, changes depending on the changing circumstances. At times, the cost of collecting fuel and starting and maintaining a fire may outweigh the potential benefits. Under such circumstances they may have chosen not to use it. This idea is complementary to, and may present an
alternative explanation for, the observation in Dibble et al. (2017) that at least in some regions Neanderthals were not using fire for very long periods of time.

**The Long View of Hominin Fire Use**

Ultimately, one of the major goals of the symposium was to instigate discussions about and perhaps reevaluate the role fire played in the evolution of the genus *Homo*. Starting at the level of the analysis of data from individual archaeological sites, we want to be able to start to construct models and hypotheses about how this process might have gone and what stages of increasing complexity might characterize it (e.g., Parker et al. 2016). An important source of data for constructing such models will come from observations of how nonhuman primates interact with natural fires (e.g., Atwell, Kovalovic, and Kendall 2015; Parker et al. 2016). Some work has already been done that indicates that some primates take advantage of natural fires and can organize their behaviors around exploiting food by-products derived by the passage of a fire (e.g., vervet monkeys; Herzog et al. 2014). Pruetz and Herzog (2017) present the results of their observations of chimpanzees in Fongoli, Senegal, interacting with wildfires. This interaction is limited, and the observed chimpanzees did not actively manipulate natural fire, but they developed an understanding of its behavior that allows them to predict its movement. Such an understanding in turn lessens their fear of it and allows them to exploit changes to the fire-altered landscape, such as accessing food resources that were altered or exposed by the fire. With the logical caveat that applying modern examples as direct analogs to the past is problematic, such research is obviously necessary if we want to develop models of early human interaction with fire that, presumably, is a required first step in the development of a more complex relationship with fire that would include active manipulation and maintenance.

Chazan (2017) proposes a model of the prehistory of fire use. He addresses one of the major problems hindering the development of a broader evolutionary view of hominin fire use: our tendency to construct narratives to describe and explain the past. The result of this tendency in the context of this topic is that we continually focus on trying to identify an “origin of fire,” looking for an event that can be pinpointed in time, after which everything changes for all hominins. Chazan’s model proposes three broad stages that would characterize the process of increasing complexity in hominin-fire interaction. The first stage involves opportunistic interaction with natural fire, and so its use was limited to where and when it was available. This could be compared to or overlaps with the chimpanzee behavior observed by Pruetz and Herzog (2017; see also Pruetz and LaDuke 2010). The second stage involves the development of fire maintenance behaviors. The third stage sees the development of fire containment strategies and presumably includes the development of techniques for creating fire. Chazan then positions these stages within the framework of *Homo* speciation. An attractive component of this model is how readily it can be operationalized—how directly researchers can develop hypotheses that are testable with archaeological data.

Finally, Sandgathe (2017) discusses two major current issues in the development of broader, more process-oriented views of the hominin fire use. The first issue is a practical one of terminology. A number of terms have come into common usage among early fire researchers (e.g., “control” and “habitual”), but there is little common understanding of what individual researchers mean by these terms, with the result that there are undoubtedly some mutual misunderstandings and a certain degree of talking past each other. The second and more important issue is the overarching tendency until recently to see the development of fire use as an event (see also Chazan 2017). In recent years another “event” has been added to this discussion: when fire use becomes “habitual.” The addition of a second, later event is a small step forward among researchers in that it starts to hint at the existence of a longer process that likely includes several major stages. However, it still fails to recognize the greater potential complexity that could have, and likely did, underlie the development of fire use. This process was undoubtedly a very long, slow one, and there is no a priori reason to assume that this development was linear, or at least was always so. The prehistory of fire use may have included multiple examples of populations not using fire after long periods of time when they did. And there is no reason to think that the process of development of fire use was the same in all regions. The big picture of the prehistory of hominin fire use was likely very messy.

**Results of the Symposium**

Over the course of the discussions that characterized the symposium a number of major issues with prehistoric fire use were identified by the discussants. These are issues that seemed to be commonly recognized by the majority if not all of the symposium participants and, presumably, by other researchers whom we were unable to invite.

First, we as a community of researchers interested in the same questions need to shift the emphasis away from discussions and debates about individual sites and what the nature of their fire residues might mean. While most of the basic data are going to continue to come from work carried out at individual sites, we need to focus more on the broader research goal of understanding the role of fire in hominin adaptations, how this evolved over time from an initial simple interaction with fire to its becoming an integral component of hominin adaptations, and the development of the technology to make it at will. This can only come from examining collectively the data from many sites. We also need to recognize the importance of integrating the rest of the archaeological data: the fire data alone will not be enough for us to understand its role in adaptations.
Second, we need to concentrate more on developing the analytical methods and skills to confidently interpret what we see in the archaeological record. Major sticking points in the debate have been identifying in very early sites, with broadly held confidence, actual fire residues and fire residues that are the product of hominin behavior. This is a basic requirement if we are to be able to identify the nature of hominin use of fire at different times and places.

These two broader goals require the acknowledgment of several other important guiding principles and considerations:

- Context is of paramount importance in interpreting the archaeological record. This is particularly important for fire residues, and a number of the papers in this volume address this issue directly (Aldeias 2017; Goldberg, Miller, and Mentzer 2017; Holdaway, Davies, and Fanning 2017; Mallol and Henry 2017). Context involves several levels of resolution as well. For example, what was the nature of vegetation cover of the site at the time it was occupied? How many years are represented by the millimeter-scale gap between two hearths in the same location? What was the substrate beneath a hearth composed of? Are the burned bones associated with a fire feature the result of cooking meat, burning bone as fuel, or simply building a fire on top of previously discarded bone? By what processes was the deposit with the fire evidence formed and altered?
- Since it is logical to assume that no scholar can be determined to have discovered the first use of fire in prehistory, this pursuit is a useless exercise in terms of what it can tell us about fire and hominin adaptations. What is important is understanding the role fire played in hominin adaptations through time and across space. In order to achieve this, the scientific community should focus on frequency of use, intensity of use, and functions of fire and the changes that took place in these aspects through time and by region.
- On their own, individual site records are of limited value, especially single occupation sites. We need to study the evidence for fire use at multiple sites and through multiple occupations to get meaningful temporal and spatial frequency data. Therefore, while some researchers do have access to multiple sites, realistically, we will only make significant progress through broad collaboration.
- We need to tailor questions to investigate available and future data. There are some important questions we would currently very much like to answer that we simply lack the data to realistically address at this point in time. For example, how, when, and where was the technology for making fire developed? Did it have a single origin? Or did it occur independently with different modalities in different areas and at different times? Getting to the point where we can confidently address these questions comes back to focusing on the development of better data-recovery methodologies and incorporating new types of data.
- A certain degree of standardization in the types of data and methods of data collection is necessary for comparability of different researchers’ data. How can we compare what different researchers are finding in the archaeological record if they individually are collecting very different types of data or using very different units of measure? How can we determine the weight of interpretations if researchers are not collecting or addressing the lack of all the pertinent data?
- We need more explicit definitions for the terminology we use so that we know what each researcher means when they discuss their data and how they have interpreted it, to eliminate unnecessary ambiguities.

Through the discussions that took place at the symposium and from reading the resulting papers, it is clear that, as with all areas of research, there are some disagreements and potential conflicts between the approaches and data that different researchers are employing in their research into early fire use. However, there is also far more common ground, and what was most obvious coming out of the symposium was the shared goal by all researchers involved to better understand the nature of the evolution of fire use in the genus Homo. We hope the symposium represents an important step in that process.

Acknowledgments
That this symposium happened at all and was such a big success is due to the hard work and support of a number of people and institutions. We are very grateful to the Wenner-Gren Foundation for Anthropological Research for the opportunity to cohost this symposium and to do so in such a beautiful locale. We are also indebted to all the participants for both the quality of their papers and the intellectual quality and collegial nature of their contributions to the discussions around the symposium table; it was a truly enjoyable and enlightening experience. We thank Meg Thibodeau for serving as such an effective rapporteur. We owe special thanks to Leslie Aiello, president of the Wenner-Gren Foundation, and Laurie Obbink, conference program associate, for their amazing patience and organizational magic. We thank all the other members of the Wenner-Gren staff who worked behind the scenes to make the symposium a success and to produce the resulting volume. And finally, while all errors in format and content in this introduction are ours, we are indebted to a number of anonymous reviewers for improving it considerably.

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Recognizing Fire in the Paleolithic Archaeological Record

by Paul Goldberg, Christopher E. Miller, and Susan M. Mentzer

Everyone agrees that fire has played an important part in the history of the genus Homo. However, because of the sometimes ephemeral and ambiguous nature of the evidence for fire in the Paleolithic record, establishing when and how hominins actively interacted with fire has been difficult. Over the past several decades, multiple techniques have been developed and employed in the search for the origins of human use of fire. Because fire is a natural phenomenon, the identification of burned remains at an archaeological site is generally not considered to be, on its own, convincing evidence for human use of fire. Rather, much of the difficulty of identifying early evidence for fire use has hinged on the question of how to establish a more direct link between burned materials and human activity. Here, we advocate for an approach to the investigation of the history of hominin use of fire that emphasizes an integration of multiple techniques. In particular, we argue that a contextualized study conducted at the microscopic scale—which we call a microcontextual approach—shows the most promise for establishing a behavioral connection between hominins and fire in the archaeological record.

Prelude

Look at figure 1. On a recent trip to the high Andes of Peru, Susan Mentzer and Chris Miller stopped to stretch their legs during the long ascent to the Puna. They pulled over onto the side of the rut-worn road and took in the sparsely vegetated landscape. “Look over there,” Susan said. “A ruined house.” Kurt Rademaker, who was leading the expedition, spoke up: “Yeah, there are lots of those up here. Some of them date to Inca or even pre-Inca times.” Mentzer and Miller got out of the truck crammed with students and equipment and headed over. The remnants of the stone walls still provided a clear outline of the structure, with obvious doorways and subdivisions of rooms. But the house had clearly been abandoned for a long time since shrubs and other vegetation now grew throughout the building.

“Hey,” Mentzer said excitedly. “Look at this! There was a bushfire!” Sure enough, many of the shrubs outside the structure had been burned, with ashes and charcoal collected in neat circles below the charred remains of branches.

“Wow,” Miller said. “Some of the shrubs inside the ruin are burned too!” Maybe it was the low oxygen of the high Andes, but their minds began to wander. Shooting each other a knowing glance, they started to think of what this ruin would look like to archaeologists in the future.

“It’s clearly a bushfire,” Miller said. “You can see where it started over there at the base of the hill.”

“Yes, but it didn’t burn evenly across the surface . . . the vegetation is patchy and so each shrub, when it burned, left a circular feature of charcoal and ash behind.”

“So it’s natural.”

“Yes, but some of the shrubs inside the house also burned and left those circular patches. You know,” Mentzer said, “in ten or twenty years, or if this site ever becomes buried, those patches would look a lot like hearths to archaeologists.”

“Yes,” Miller said, a bit despondently.

“And these burned patches are natural, but they are associated with an archaeological site. And since the burned patches are inside the structure, it would be easy to assume that they are hearths,” Mentzer said.

“Yes,” Miller said again. “But how could archaeologists distinguish between a natural fire like this and a hearth?”

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vated material remains and human activities and behavior. In sites from most time periods, the evidence for anthropogenic fire can appear to be quite convincing: constructed hearths, kilns, and other installations can be readily compared with analogous features known from historic and ethnographic studies (Gur-Arieh et al. 2013). Similarly, the presence of ceramic sherds, glass, bricks, metal, and slag all clearly point to the control of fire for craft and industrial practices in the past.

Archaeological evidence for the use of fire becomes spottier when dealing with hunter-gatherer or other non-sedentary societies, particularly those from the Pleistocene. Although some Upper Paleolithic people lined and paved their hearths with clay and stone (Karkanas et al. 2004; Movius 1966), thus making them more readily identifiable by archaeologists, most evidence for fire in the Pleistocene takes the form of scatters and concentrations of charcoal, ash, burned bone, heated stone, and reddened substrates. Recognizing and interpreting these materials as evidence for use of fire, let alone control or production of fire, can be difficult (see Sandgathe 2017 for definitions of use, control, and production of fire). Furthermore, this difficulty is only compounded the farther back in time we look when we search for the origins of hominin interactions with fire.

The evidence for fire that we encounter in the archaeological record can be different from many other types of artifacts found at Paleolithic sites. Unlike handaxes, cave paintings, or butchered bones, materials such as charcoal, ash, and other burned remains can be produced by humans but also by natural processes. Evidence for naturally occurring fires in the form of preserved charcoal is known from the geological record dating to the Devonian, more than 350 Mya (Scott 2000). Similarly, Bordes (1957) reports evidence for heated chert from deposits dating to the Miocene. Fire is essentially a natural chemical reaction that humans have learned to anticipate, use, control, and produce.

The difficulties of first identifying heated materials in the Paleolithic record and second determining whether humans were the agents responsible have been recognized by archaeologists since at least the mid-twentieth century (Oakley 1954). Later researchers, in particular Barbetti (1986), formalized the problem: “Demonstrating that fire was used at an archaeological site is a two-step process. One must first find the evidence and show that fire was present. It is then necessary to demonstrate that it was associated with human activity” (771).

In the 30 years since Barbetti laid out the two-step process of evaluating evidence for fire in the archaeological record, many new methods and techniques have been introduced that aid in identifying burned materials at Paleolithic sites. Similarly, many new sites have been excavated and novel studies conducted that help us evaluate the nature of the association of burned materials and human activity. However, despite these advances, Barbetti’s two-step approach should still form the foundation for any archaeological study of fire.

Therefore, in this paper, we have decided to revisit and expand on Barbetti’s arguments, focusing on how we address the following three questions about materials encountered in

1. This is a fictionalized account of a true event. The dialogue has been changed and some literary license has been taken, but the scientific concerns are real.

Introduction

Fire—as with any aspect of the past studied by archaeologists—requires us to establish clear theoretical links between exca-
archaeological sites: (1) Are they burned? (2) Were they recovered from the primary location of heating, and if not, what is the nature of their deposition? and (3) Were they burned by humans?

We will present a range of approaches to identifying heated materials from archaeological sites. But we will also show how positive results—those that show that materials have been heated—do not alone constitute sufficient evidence for human use of fire. Rather, we argue that these techniques need to be applied in conjunction with high-resolution analyses of site formation processes in order to form a link between material evidence for heating and human behavior.

The Microcontextual Approach

The microcontextual approach was put forward by Goldberg and Berna (2010) from concepts developed by researchers such as Boivin (2004), Goldberg and Macphail (2006), Matthews (2005), and Matthews et al. (1997). It is essentially the in situ analysis of microscopic components in thin section using a variety of microanalytical techniques. The microcontextual approach provides a framework for the integration of these data by extending the context of an archaeological artifact—its matrix, its provenience, and its associations with other artifacts (Renfrew and Bahn 2007)—to the microscopic scale. In this framework, we treat individual particles of anthropogenic sediments as artifacts and microscopic deposits as assemblages (fig. 2). This approach has proven successful in the analysis of combustion features and burned materials in sites of all ages, ranging from the Paleolithic (Goldberg and Berna 2010) to the Iron Age (Mentzer, Romano, and Voyatzis 2015; Toffolo et al. 2012).

The most effective and efficient way to monitor and control for (micro)context is the use of soil micromorphology (Courty, Goldberg, and Macphail 1989; Goldberg and Macphail 2006; Macphail and Cruise 2001), which is the meso- and microscopic analysis of intact blocks of sediments or soils that have been indurated, sliced, polished, and prepared into thin sections (Courty, Goldberg, and Macphail 1989). Observations made on micromorphological samples can include the mineralogical and organic composition of sedimentary components; the size, shape and sorting of grains; the porosity and microstructure of deposits; the presence of bedding or other microscopic sedimentary structures; and the fabric—the internal organization of all these attributes (Bullock et al. 1985; Courty, Goldberg, and Macphail 1989; Stoops 2003). Furthermore, micromorphological analysis can reveal both physical and chemical postdepositional alteration of deposits that may be related to either natural or human agents. Anthropogenic physical alteration might include trampling or reworking of combustion residues by dumping, middening, or hearth rake out. Natural, chemical alteration might entail dissolution of ashes or bone or the secondary precipitation of carbonates or phosphates. Because the use of micromorphology facilitates the analysis of postdepositional alteration and enables the distinction between natural and anthropogenic sediments, it is widely used as a first-order approach to the study of combustion features and burned materials (Berna and Goldberg 2008; Mentzer 2013; Miller, Goldberg, and Berna 2013).

A number of additional microanalytical techniques outlined in table 1 can be conducted on either loose sediment or materials present in micromorphism samples. Ideally, a study of evidence for fire applies the same techniques on both loose and micromorphological samples, thereby supporting the integration of results obtained microscopically with observations made at the site scale. Defined narrowly (or optimistically), a microcontextual approach to the study of a combustion feature might mean that every analysis conducted as part of the study should be conducted directly on materials visible in a micromorphological thin section or in its corresponding indurated sediment block.

Micromorphology and a microcontextual approach can also be used as a type of “methodological filter” for determining which additional techniques could be applied to identify heating and to assess the depositional association of heated materials with other traces of human activity. In the possible combustion feature illustrated in figure 2, observation of three types of potentially heated material and fuel residues as well as anthropogenic inclusions (fig. 2B) lead to an analytical trajectory that includes micro-FTIR (μ-FTIR; Fourier transform infrared spectroscopy), organic petrology, and the scanning electron microscope (SEM; fig. 2E). Similarly, the microcontextual approach can also help discourage the use of certain other techniques that may be unnecessary or produce misleading results. In the same example, the observation that the suspected ashes have been chemically altered (fig. 2C) precludes the measurement of stable isotopes of carbon and oxygen from the calcareous ashes (Mentzer and Quaid 2013). A microcontextual study ideally does not focus on a single feature or only on potential evidence for human use of fire. Rather, microcontextual analyses should be part of a broader geoarchaeological study that attempts to understand how potential evidence for use of fire fits within a holistic site formation model.

Examples

Roebroeks and Villa (2011), in their assessment and ranking of sites containing evidence for early use of fire, give particular weight to studies that identify combustion features. In particular, they privilege studies that employ micromorphology or use multiple analytical techniques over those that rely on only one method or on one line of evidence. The microcontextual approach, by providing a methodological and theoretical link between multiple analytical techniques and micromorphology, is therefore ideally suited for the study of Paleolithic fire. In practice, this has only been carried out to a limited extent.

Many of the techniques for studying burned materials were developed first using loose sediment samples, and only recently have they been applied to micromorphological samples. For example, Shahack-Gross et al. (2008) first investigated the
Figure 2. Application of the microcontextual approach to a suspected combustion feature. A, Middle Stone Age deposits in the site of Sibudu, South Africa, contain discrete features (arrow) that appear in the field to be composed of charred material overlain by ashes. These features were sampled for micromorphological analysis. For more detailed information about the micromorphology at this site, see Goldberg et al. (2009). B, Thin section prepared from a different feature but with similar characteristics (incident light scan). The area photographed in parts C and D is indicated with the red box. C, Feature viewed using a petrographic microscope (plane-polarized light; PPL) can be likened to a microscopic stratigraphic section containing what appears to be a basal layer of rubifi ed sediment (Ru) overlain by charred plant fragments (Ch) and topped with ashes (Ash). The sequence also contains microscopic artifacts such as bone fragments (B) and lithic debitage (L). The depositional history of the three layers is clear at this scale of observation. The contacts are gradational over several millimeters with no indication that they are derived from discrete depositional events. This relationship is consistent with a formation model for intact hearths proposed by Meignen et al. (2001). Each of the materials visible in this feature can be analyzed using additional techniques described in table 1. The bone fragments and charred plants can be analyzed using organic petrology. The ash layer can be investigated at higher resolution using a petrographic microscope or SEM, which facilitates morphological identifications of different components (e.g., ash rhombs, phytoliths). The molecular and elemental compositions of the bones
isotopic composition of ashes using experimental materials and archaeological samples from the site of Amud Cave (Israel). This approach was extended to micromorphological samples several years later (Mentzer and Quade 2013). Moreover, until recently, many microanalytical instruments were available to archaeologists on a limited basis. Nevertheless, there are a few cases in which a microcontextual study was conducted on Paleolithic fire features (Berna and Goldberg 2008; Berna et al. 2012; Goldberg and Berna 2010; Lowe et al. 2016; Mallol, Mentzer, and Miller, forthcoming; Shahack-Gross et al. 2014; Stahlschmidt et al. 2015). Here, we draw on several examples from three Lower Paleolithic sites to illustrate how the approach can yield positive, negative, and ambiguous results. At the end, we highlight an application where we believe the approach is most promising: in the analysis of traces of fire that have been affected by postdepositional processes.

**Positive Results from Qesem Cave**

Microcontextual analyses have been essential in establishing some of the earliest clear evidence for repeated use of fire by humans. At Qesem Cave (Israel), which is associated with an Acheulo-Yabrudian occupation that dates between ca. 400 and 200 kya (Barkai et al. 2003; Gopher et al. 2005; Karkanas et al. 2007), researchers conducted a micromethod study that relied heavily on micromorphology but was augmented with other techniques, such as FTIR analysis on loose sediment samples and bones and isotopic analysis of calcareous deposits. The analysis on loose sediment samples returned negative or ambiguous results. For example, FTIR analysis of loose sediment did not reveal any evidence that the clay fraction of the cave deposits had been heated to above 500°C. In addition, no phytoliths or siliceous aggregates were found in the acid-insoluble fraction of the loose samples, possibly reflecting unfavorable preservation conditions in the alkaline environment of the cave. However, in thin section, Karkanas et al. (2007) identified clear evidence for fire in the form of numerous examples of calcareous ashes. The authors reported that at a microscopic scale, the ashes were found in discrete layers, generally 2 cm thick and in association with small fragments of burned bone and clay-rich soil aggregates that appeared reddened and probably heated. Supporting the micromorphological evidence for fire at the site, FTIR analysis of bone showed that some fragments contained pyrolyzed collagen, and some were calcined. Similarly, carbon and oxygen isotopic analysis suggested that at least some of the deposits at the site consisted of recrystallized ashes or a mixture of ashes and geogenic calcite.

At Qesem, a combination of micromorphology, FTIR, and isotopic analyses clearly demonstrated the presence of fire. However, it was the contextualization of these analyses at the microscopic scale that allowed the authors to demonstrate that the burned remains were probably related to human behavior. Karkanas et al. (2007) point out that some authors (e.g., Harrold and Otte 2001) argue that natural fires, such as those caused by lightning strikes or spontaneous combustion of guano, could account for the presence of burned materials in caves. In contrast, Karkanas et al. (2007) argue that spontaneous combustion is unlikely because these types of fires require significant amounts of organic material that were generally absent from the deposits. Additionally, guano fires, according to the authors, burn at relatively low temperatures and do not produce completely combusted remains. At Qesem, much of the evidence for fire consists of completely combusted wood (in the form of ashes) and charred and calcined bones, which generally would be expected to occur with higher-temperature fires. The most convincing argument is that small fragments of burned bone are found in thin, discrete lenses composed of pure ash. The micromorphological study documented the repetitive occurrence of these distinct “microcontexts” throughout the sequence at Qesem, thereby providing strong evidence for the repeated use of fire by the site’s inhabitants.

A further study at Qesem (Shahack-Gross et al. 2014) focused on a 300 kya stone-lined feature and employed a broader range of microcontextual analyses. The ca. 4 m² feature was lined by a ring of rocks and contained laminated deposits within it (Shahack-Gross et al. 2014). In addition to micromorphology and FTIR analysis on loose sediment samples from the laminated deposits, the authors also conducted μ-FTIR measurements directly on thin sections including bone fragments and soil aggregates. These measurements confirmed that the bone fragments found in association within the laminations of ashes were burned to above 500°C. The authors also demonstrated the presence of clay aggregates that had been heated to above 400°C. The identification of heated clay aggregates using μ-FTIR in the ash laminations shows in particular the strength of the microcontextual approach because previous FTIR analysis of loose sediments did not provide any clear evidence for heating of clays above 500°C at the site.
Table 1. Geoscientific analytical techniques for the study of ancient fire

<table>
<thead>
<tr>
<th>Analytical technique, sample type</th>
<th>Type of information/data</th>
<th>Used to identify presence/absence of heating?</th>
<th>Other information</th>
<th>Key references</th>
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<tr>
<td>Micromorphology:</td>
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<td>Oriented blocks of sediment</td>
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<td>indurated with resin and</td>
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<td>processed into petrographic thin</td>
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<td>sections</td>
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<tr>
<td>Visual observation of sediment</td>
<td></td>
<td>Yes. Can be used to identify some by-products</td>
<td>Allows the analyst to</td>
<td>Canti 2003;</td>
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<td>components using a petrographic</td>
<td></td>
<td>of combustion based on mineralogical</td>
<td>observe the spatial</td>
<td>Courty,</td>
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<td>microscope and different sources</td>
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<td>composition and morphology (e.g., ashes).</td>
<td>relationship between</td>
<td>Goldberg,</td>
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<td>of light (plane-polarized, cross</td>
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<td>different components</td>
<td>Macphail 1989;</td>
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<td>polarized, darkfield, fluorescent,</td>
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<td>of the feature.</td>
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<td>reflected, oblique incident)</td>
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<td>Fabric and structure</td>
<td>Macphail 2003;</td>
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<td>interpretations about</td>
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<td>depositional context.</td>
<td>Romano,</td>
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<td>Other components</td>
<td>Voyatzis 2015;</td>
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<td>provide information</td>
<td>Wattez 1988</td>
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<td>FTIR:</td>
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<td>Loose sediment samples</td>
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<td>Heated lithics and rocks</td>
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<td>In situ measurements on intact</td>
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<td>blocks and thin sections collected</td>
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<td>using μ-FTIR</td>
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<td>Type and strength of molecular</td>
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<td>Yes. Certain materials (e.g., clay minerals,</td>
<td>Provides temperature</td>
<td>Berna et al.</td>
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<td>bonds; output in the form of</td>
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<td>bone) can be analyzed to document molecular</td>
<td>ranges of heating</td>
<td>2007; Forget et</td>
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<td>spectra</td>
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<td>changes that occur with heating.</td>
<td>for bone and clay</td>
<td>al. 2015;</td>
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<td>minerals; can also</td>
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<td>be used to identify</td>
<td>Bena 2010;</td>
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<td>primary and secondary</td>
<td>Regev et al.</td>
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<td>minerals. Under ideal</td>
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<td>preservation</td>
<td>Thompson,</td>
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<td>conditions, pyrogenic</td>
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<td>calcite can be</td>
<td>Bonniere 2013;</td>
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<td>Weiner 2010;</td>
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<td>Xu et al. 2015;</td>
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<td>XRD:</td>
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<td>Loose sediment samples</td>
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<td>and artifacts (bone, lithics)</td>
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<td>In situ measurements on micromor-</td>
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<td>morphological samples using micro-</td>
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<td>Spacing and arrangement of atoms</td>
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<td>Yes. Certain materials (e.g., clay minerals,</td>
<td>Can be used to identify</td>
<td>Domanski and</td>
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<td>in a crystal lattice; output in</td>
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<td>bone) can be analyzed to document molecular</td>
<td>primary and secondary</td>
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<td>the form of diffraction patterns</td>
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<td>changes that occur with heating.</td>
<td>minerals. Can be used</td>
<td>Rogers and</td>
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<td>to study heat treatment of</td>
<td>Daniels 2002;</td>
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<td>lithic materials.</td>
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<td>SEM-EDS:</td>
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<td>Loose sediment samples</td>
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<td>In situ measurements on polished</td>
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<td>or carbon-coated micromorphologi-</td>
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<td>Spacing and arrangement of atoms</td>
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<td>No.</td>
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<td>Karkanas 2010;</td>
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<td>in a crystal lattice; output in</td>
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<td>Karkanas et al.</td>
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<td>the form of diffraction patterns</td>
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<td>Phytolith analysis:</td>
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<td>Phytoliths extracted from loose</td>
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<td>In situ observation of phytoliths</td>
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<td>visible in micromorphological</td>
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<td>samples</td>
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<td>Qualitative description of phyt-</td>
<td></td>
<td>Yes. Measurements of the refractive</td>
<td>Identification of</td>
<td>Albert, Berna,</td>
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<td>lith morphology; quantitative</td>
<td></td>
<td>index of individual phytoliths can be used</td>
<td>phytoliths to plant</td>
<td>and Goldberg</td>
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<td>information from analysis of</td>
<td></td>
<td>to determine heating</td>
<td>type based on</td>
<td>2012; Albert</td>
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<td>populations</td>
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<td>morphology can be</td>
<td>and Cabanes</td>
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<td>used to study the</td>
<td>2007; Albert et</td>
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<tr>
<td>Analytical technique</td>
<td>Sample type</td>
<td>Type of information/data</td>
<td>Key references</td>
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<td><strong>Organic petrology:</strong></td>
<td>In situ measurements on polished, resin-indurated block sediment samples</td>
<td>Identification of microscopic fragments of plants based on morphology, reflectance measurements of tissues and gels, and quantitative fluorescence</td>
<td>Yes. Charred plant tissues have reflectance values that are different from those of humified tissues. Provides information about fuels and their state of decomposition before burning. Clark and Liguéis 2010; Goldberg et al. 2009; Stahlschmidt et al. 2015; Suárez-Ruiz 2012</td>
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<td>Other materials (e.g., bones) mounted in epoxy and polished</td>
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<td>Electron spin resonance:</td>
<td>Measurement of the g-value of charred organic component of bone</td>
<td>Yes. Heated bones have characteristic ESR spectra. Can be used to reconstruct heating temperature. Michel, Falguères, and Dolo 1998; Schurr and Hayes 2008</td>
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<td></td>
<td>Theroluminescence on heated flints or sediment</td>
<td>Measurement of the amount of radiation damage sustained by a material following a heating event</td>
<td>Yes. Heated materials have a measurable luminescence signal. Can be used to study heat treatment of lithic materials. Both techniques provide ages for burning events. Brodard et al. 2012; Mercier et al. 2007; Richter 2007</td>
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<td>Optically stimulated luminescence on heated sediment</td>
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<td>Magnetic measurements:</td>
<td>Enrichment in ferromagnetic minerals are visible as magnetic anomalies. Magnetic susceptibility is a measure of the abundance of magnetized grains within sediment. Measurements of remnant magnetism can indicate whether rocks were heated in the past</td>
<td>Yes. Heated sediments have higher magnetic susceptibility than unheated sediments. Iron-bearing minerals in heated rocks record the intensity and direction of the magnetic field at the time of burning. Magnetic susceptibility measurements can be complicated by soil forming processes with equilibrity producing ambiguous results in some cases. Components of magnetization can be used to determine heating temperatures. Paleomagnetic measurements can be used to determine whether burned rocks are in situ. Barbetti 1986; Bellomo 1993; Dalin and Banerjee 1998; Gose 2000</td>
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<td>Magnetic field survey on buried features (magnetometry)</td>
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<td>Magnetic susceptibility on loose sediment samples</td>
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<td></td>
<td>Palaeomagnetism on heated rocks</td>
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<td><strong>Organic chemistry:</strong></td>
<td>Gas chromatography mass spectrometry on sediment containing organic material</td>
<td>Identification of alkanes from plants and fatty acids from burned animal tissues</td>
<td>Yes. Chartering reduces the relative abundance of long-chain n-alkenes. May be useful for identifying residues from cooking or animal processing and conditions of heating. Applications are thus far limited to Holocene contexts. Almendros, Martin, and Gonzalez-Vila 1988; Buonasera 2005; Buonasera et al. 2015; Eckmeier and Wiesenberg 2009; Maillot et al. 2013; March 2013; March, Ferreni, and Guez 1993; Sistiaga et al. 2011</td>
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<td></td>
<td>Quasi in situ measurements on powders drilled from micromorphological blocks</td>
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</table>

a FTIR = Fourier transform infrared spectroscopy.

b XRD = X-ray diffraction.

c SEM/EDS = scanning electron microscopy/energy-dispersive X-ray spectroscopy.
Combining field observations with the results of the microcontextual study, the authors could convincingly argue that the feature probably represented a large-scale hearth that was repeatedly used and around which various activities were conducted. Taken together, the studies by Karkanas et al. (2007) and Shahack-Gross et al. (2014) suggest that fire was repeatedly used by humans at Qesem. Furthermore, the authors could also show that the way in which the occupants engaged with fire changed over time. Although different techniques such as micromorphology, FTIR, and isotopic analysis could reveal the presence of heat-altered remains at Qesem, it was the integration of these data within a microcontextual research framework that allowed the authors to make clear behavioral inferences regarding hominin interactions with fire in the past (Barkai et al. 2017).

**Negative Results from Schöningen and Zhoukoudian**

Other microcontextual studies have shown that some Paleolithic sites that were reported and widely cited as containing evidence for fire in fact do not. One such case is Schöningen (Lower Saxony, Germany), an open-air Lower Paleolithic site dating to ca. 300 kya that is renowned for its excellent organic preservation, including wooden hunting implements. Thieme (1997, 1999) presented several lines of evidence for anthropogenic fire at Schöningen, including four purportedly burned wooden implements as well as several features that he called Feuerstellen, or hearths. These features consisted of localized reddened areas of calcareous marl that were on average 1 m² in size. Excavators noted that there were no obvious remains of charcoal or ash. In a preliminary micromorphological study of the features, Schiegl and Thieme (2007) suggested that the evidence for fire alteration of the substrate was ambiguous based on the presence of mollusk shells that had not been heat altered.

Expanding on the initial study of the features by Schiegl and Thieme, Stahlschmidt et al. (2015) conducted a more detailed microcontextual analysis employing micromorphology, FTIR and μ-FTIR, organic petrology, mineral magnetic parameters, and thermoluminescence. Their analysis of the reddened areas showed that these features consisted of a thick, consolidated crust of iron oxide that impregnated the calcareous lake deposits of the substrate. In thin section, the reddening observed in the field appeared to correlate with sediment staining and matrix impregnations of hematite, which result from natural redox processes (Lindbo, Stolt, and Vepraskas 2010). In direct association with the hematite were calcareous lake sediments and calcareous fragments of mollusk shells, which suggest that the substrate could not have been heated above 500°C. Similarly, the presence of kaolinite within the feature, which was identified using FTIR analysis, suggested that the substrate had never been heated above 400°C. A study of experimentally heated sediment collected from Schöningen suggested that the degree of reddening observed in the features would occur only at higher temperatures. Additionally, the thermoluminescence study showed that the lithological character of the sediment within the features did not differ significantly from those outside of the features. Finally, none of the mineral magnetic parameters recorded from the sediment samples from the features corresponded with parameters measured from control samples of the calcareous lake deposits that were experimentally heated. The results of this study strongly suggested that the reddened features formed as a result of natural oxidation of the iron sulfide (pyrite) and organic material in the lake deposits. This process was probably induced by the artificial lowering of the water table at Schöningen during mining operations in the late twentieth century.

The Schöningen microcontextual study did yield some evidence for fire at the site, but the authors argue that it was probably not related to human behavior. Sand-size fragments of charcoal are present within the features. However, organic petrographic analysis of these fragments showed that the charcoal was not derived from wood but rather was composed of rounded fragments of peat. The authors argued that these fragments came from natural peat fires and were subsequently redeposited in the lake.

Similarly, the site of Zhoukoudian, Locality 1 (China), has long been cited as representing early evidence for fire since its initial excavations in the 1920s and 1930s: the presence of burned bones and reddish layers were reported from both Layers 10 and 4 and were interpreted as hearths (Black 1931; Jia-Chia 1980; Jia and Huang 1990; Teilhard 1934; Wu and Lin 1983). Micromorphology and FTIR analysis of the sediments and features in both layers (Goldberg et al. 2001; Weiner et al. 1998) suggested that they were not related to heating. Layer 10 consists of finely laminated silt and clay interbedded with yellow and reddish brown organic fragments with localized fragments of limestone; charcoal was not observed in the field. The finely laminated nature of the Layer 10 deposits is consistent with low energy water or ponded deposition by the Zhoukoudian River, which at that time entered the cave. In the field, channeling and erosion of Layer 10 is clearly visible. Additionally, the deposits of Layer 10 completely lack the red-black-white structure of a combustion feature or hearth (Goldberg et al. 2001; fig. 2). Micromorphological analysis also demonstrated that the reddening of Layer 4 is a result of diagenesis evidenced by the presence of fine, silt-size grains of hematite. These grains probably formed during a period of subaerial exposure after the roof of the site had collapsed. Moreover, FTIR and elemental analyses revealed no evidence of heat alteration of the limestone (Weiner et al. 1998). However, new data from recent excavations presented by Gao et al. (2017) may reveal the presence of indisputable fireplaces.

**Ambiguous Results from Wonderwerk**

Whereas the microcontextual studies at Zhoukoudian and Schöningen clearly demonstrated absence of evidence for anthropogenic fire and the study at Qesem produced clear evidence for repeated use of fire, other microcontextual studies
have produced results that are more difficult to interpret. At Wonderwerk Cave (Northern Cape, South Africa), Berna et al. (2012) presented several lines of evidence for heated materials from a single layer dated to ca. 1.0 Ma. The study integrated micromorphology with μ-FTIR, FTIR analysis of excavated bone fragments, and lithic analysis. The authors report potlidied lithics, which they interpret as having fractured as a result of heating, probably above 500°C. In addition, they noted that bones recovered during excavation exhibit colors that are consistent with bones that have been exposed to heat (Stiner et al. 1995). FTIR analysis of several of these bones demonstrated that they were heated to above 400°C, and additionally some altered clay adhering to a gray-colored bone suggested heating of the clay to somewhere between 400°C and 700°C. FTIR spectra collected on white bone fragments did not contain peaks that would indicate the high temperatures that are typically associated with calcination (Thompson, Islam, and Bonniere 2013). In micromorphological samples, Berna and colleagues (2012) identified pseudomorphic grains of oxalate crystals composed of calcite, which the authors identified as ashes following (Canti 2003; Wattez 1988); however, Berna et al. (2012) and Goldberg, Berna, and Chazan (2015) note that calcified plant remains in the form of rhizoliths and other plant fragments are also present in the same deposits, suggesting that the formation history of these layers may be complex. Additionally, μ-FTIR analysis conducted directly on the thin sections identified bone that was also heated to between 400°C and 550°C.

The authors employed microcontextual analyses to identify the presence of heated materials at Wonderwerk Cave. To address the association of this evidence with hominin behavior, they considered both microscopic and site-scale formation processes of the deposits in question. The authors first addressed whether the burning could have occurred independently of human activity. They argued that because the burned materials are distributed throughout a thick archaeological stratum, it is unlikely that wildfires could have repeatedly extended deep into the cave from the surrounding landscape. Second, they noted that whereas none of the burned materials were recovered in primary position, the angularity of the bone and ash fragments observed in thin section rules out the possibility that these materials were transported into the cave by natural processes. Berna et al. (2012) point out that without a clear combustion feature, it is difficult to demonstrate hominin control of fire (Roebroeks and Villa 2011). However, they argue that there is a clear association of human activity and fire at Wonderwerk, implying human knowledge, if not use, of fire in the cave.

Difficult Cases: The Levantine Middle Paleolithic

In the three types of scenarios described above, microcontextual studies have contributed to answering the three questions about burned materials that were raised at the beginning of this paper. We feel that in addition to linking humans to burned materials, the microcontextual approach is instrumental in cases where less-than-ideal preservation conditions at Paleolithic sites have greatly altered the evidence for human use of fire. Indeed, many of the analytical techniques that we champion in earlier sections of this paper were developed for the study of combustion features affected by chemical diagenesis and physical reworking or a combination thereof at the Levantine Middle Paleolithic sites of Kebara, Hayonim, and Amud (Berna and Goldberg 2008; Schiegl et al. 1994; Weiner, Goldberg, and Bar-Yosef 2002; Weiner et al. 1995, 2007). In each of these sites, research teams expanded on an initial desire to document the presence of burned materials in primary or secondary position, first integrating micromorphological studies with mineralogy and chemical analyses and later microsampling the intact features for other types of microscopic artifacts, such as phytoliths. In this way, these sites served as laboratories for the development of analytical techniques that, thanks to recent improvements in instrumentation, can now be directly applied to micromorphological samples (see table 1).

At the sites of Kebara and Hayonim, evidence for fire seems readily apparent in the field (Meignen, Goldberg, and Bar-Yosef 2007; Meignen et al. 2001), where the most obvious expression is structured combustion features consisting of a sometimes rubified basal substrate overlain by a charcoal-rich zone, which is capped by calcareous or diagenetically altered ashes consisting of apatite (dahllite) and other phosphate minerals (Meignen et al. 2001). In profile, these features vary from centimeter- to decimeter-diameter lenses (e.g., Hayonim Cave) to thin, centimeter-thick stringers within depressions. In plan view the features are generally circular (Berna and Goldberg 2008; Goldberg and Bar-Yosef 1998; Meignen, Goldberg, and Bar-Yosef 2007), although at Amud Cave, only the cemented ashly portions of the tripartite sequence of combustion features seem to have survived, the rest of the sediments having been homogenized by bioturbation (Berna and Goldberg 2008; Meignen, Goldberg, and Bar-Yosef 2007; Meignen et al. 2001). At Kebara and Hayonim, similar vertical sequences of basal rubification, burned organic matter or charcoal, and ashes can be seen in thin section, which also reveals repeated stacking of combusted layers that are not evident in the field.

In the field, many of the features were identified as obvious combustion residues. Other features reveal an important caveat in trying to evaluate the former presence of fire because of diagenesis: the physical and chemical changes following deposition. In Kebara and Hayonim, some of the original components, especially calcareous ashes, dissolved or were transformed into other minerals, such as phosphates (Berna and Goldberg 2008; Schiegl et al. 1994, 1996; Weiner, Schiegl, and Bar-Yosef 1995; Weiner et al. 1995, 2007). Although these changes can be readily observed in the field where the original combustion structures still exist (e.g., Kebara Cave; Meignen, Goldberg, and Bar-Yosef 2007), other components, such as bone, have been completely dissolved (Goldberg et al. 2007; Schiegl et al. 1994; Weiner, Goldberg, and Bar-Yosef 1993, 2002; Weiner et al. 1995). Based on the typical sequence of rubified sediment overlain by charcoal and ashes that was documented in better-preserved areas of the sites (Meignen et al. 2001),
similar features containing phosphate minerals and amorphous silicates instead of ashes were interpreted as hearths affected by diagenesis.

In addition to micromorphology, a number of other techniques were employed to confirm the presence of anthropogenic fire within the sites. In Kebara Cave, researchers documented not only the presence of numerous hearth structures but also the occurrence of wood phytoliths, which would not have accumulated within the cave naturally (Albert, Berna, and Goldberg 2012; Albert et al. 2000). Furthermore, wood phytoliths also occur in cave sediments that do not contain hearth structures that are visible in the field; these types of phytoliths are absent from control samples of terra rossa collected outside the site. In Amud Cave, phytoliths from calcareous ashes and surrounding sediments were studied using micromorphology and stable isotope analysis. The phytoliths were predominantly from wood (including palm and fig), whereas grass phytoliths, which are fresh and composed of spikelets, were thought to have been brought into the cave and accumulated within the anthropogenic ashy units (Madella et al. 2002). Thus, the ubiquitous presence of wood phytoliths in ashes suggested that these siliceous materials could be an indication of fireplaces in cases when the more soluble calcitic component might have been dissolved.

One of the most important things to come out of the Levantine cave studies was an improved understanding of the microscopic expression of burned materials in different depositional contexts. The fabric and structure of burned materials, which are visible in thin section, can help one determine whether the burned materials (1) are in their original place; (2) have been reworked locally by natural processes such as bioturbation (Berna and Goldberg 2008; Goldberg and Bar-Yosef 1998; Madella et al. 2002), colluviation, or runoff (Goldberg et al. 2007); or (3) have been reworked by human activities, such as dumping or hearth rake out (Goldberg 2003; Kuhn et al. 2009; Meignen, Goldberg, and Bar-Yosef 2007; Miller 2015; Schiegl et al. 2003). At the site of Kebara, a large concentration of ashes in the rear of the cave was interpreted as a midden only after micromorphological analyses ruled out other agents of redeposition. Such evidence for intentional collection and movement of burned materials within the living environment not only provides an indirect marker of human intentionality in the control and maintenance of fire but also shows that this behavior was repeated over long periods of time.

Many of the techniques that, when combined, form the basis of a microcontextual analysis of a combustion feature, were developed during the decades-long excavations at these sites. In Kebara and Hayonim Caves, mineralogical analyses were classically carried out using FTIR in the field on bulk sediment samples that were ground and made into a pellet using KBr as a binder; supplemental confirmations followed in the laboratory using X-ray diffraction (XRD; e.g., Weiner, Goldberg, and Bar-Yosef 1993; Weiner et al. 1995, 1998). Within the past decade, however, it became clear that certain contextual evidence was lost using bulk samples, even if they were collected as <1 g samples in the field: it was not readily apparent what was really being measured. For example, apatite in a sediment sample could be sand- or silt-size fragments of bone or a secondary precipitate. Thus, in order to have an idea of what is actually being analyzed in the sample, researchers have developed new microanalytical techniques such as µ-FTIR and micro-XRD (µ-XRD; Berna, forthcoming; Berthold and Mentzer, forthcoming). Although these techniques were not available at the time, similar microcontextual analyses were conducted directly on thin sections from Kebara and Hayonim using SEM/energy-dispersive X-ray spectroscopy (SEM/EDS; Schiegl et al. 1996). Kebara Cave was also the site of one of the first studies to integrate phytolith analyses from loose samples with micromorphology of combustion features (Albert, Berna, and Goldberg 2012), an approach that was recently extended to include phytolith identifications in thin section (Wadley et al. 2011).

Despite these methodological advances, true microcontextual studies from the Levantine “laboratory” sites are limited. However, a test case for the microcontextual approach was developed for the site of Kebara and presented by Berna and Goldberg (2008). They analyzed a large, well-structured hearth containing an organic-rich layer with bones overlain by ashes with both micromorphology and µ-FTIR, which provided temperature estimates of the different components: (a) combusted plant fuel, heated at ~300°C, and the included burned bones heated at ~300°C; (b) the overlying <1 mm thick accumulation of phosphatized calcitic ashes with (c) inclusions of calcined bone heated at ≥550°C, and (d) burned soil particles heated at ≥500°C. These results yield evidence of heating of various components within the different parts of the hearth structure and also provide additional FTIR data to corroborate previous studies of the diagenesis of the features (e.g., Schiegl et al. 1996; Weiner et al. 2007). This work demonstrates how such an approach yields a more holistic picture of the conditions of formation and preservation of hearths.

**Approaches to Recognizing Heated Archaeological Materials**

Steps toward positive recognition of fire in the Paleolithic archaeological record take place in both the field and in the laboratory. The field is the first place where the context of possible burned material can be established, including the mutual associations among objects and features as well as their connection to the deposits that contain them.

In the field, one can note possible indicators of in situ fire, including rubification of sediments, the presence of ashy sediment, charcoal and char, and other burned objects, such as fire-cracked rock and burned or calcined bone. In younger sites intact, structured features, such as pits (including stone-lined or plastered pits; e.g., Thoms 2008, 2009) can be primary combustion features. Mounded accumulations and middens can also be loci of reworked combusted materials, like those ob-
served at sites such as Kebara and Uçağzıh (e.g., Goldberg 2003; Kuhn et al. 2009; Meignen, Goldberg, and Bar-Yosef 2007).

Fieldwork aimed at recovering data about fire should be focused on observing the setting of the site and its lithostratigraphy. For example, noting the shape, size, nature, and context of suspected burned zones may be helpful for deciding whether a reddened zone is the result of heating or diagenesis (Cushing et al. 1986; Pigati et al. 2014).

In addition, objects and features should be recorded precisely in the field using, for example, a theodolite system (Dibble and McPherron 1988; McPherron and Dibble 2002; McPherron, Dibble, and Goldberg 2005). This or a similar type of strategy provides both accurate 3-D data on objects, features, and samples and also virtual real-time data in the field to assess the integrity of deposits, as well as the location and context of samples collected for further analysis in the laboratory.

Laboratory analyses are needed to supply qualitative and quantitative data that, when combined with field observations, can document—or at least suggest—the former presence of fire. The materials Paleolithic archaeologists often cite as evidence for past fire include ashes, charcoal, burned bone, heated (often reddened) substrates, and fire-altered rocks; most of these materials are initially identified in the field. For example, a deposit that appears grayish and silty is described as ash, black flecks encountered during excavation are called charcoal, black and white bones are termed charred and calcined, and reddened patches of sediment are fire-altered substrate. Although these types of observations provide the first line of evidence for the possible presence of fire at an archaeological site, on their own, field observations are not sufficient to demonstrate heating, let alone human use of fire. This is because interpreting these field observations is confounded by equifinality: the characteristics that we most often use to identify potential fire evidence in the field are not solely produced by fire. For example, most field identifications of burned materials—following guidelines that we advocate (e.g., Meignen et al. 2001)—are based on color: charcoal is black, burned bone is black or white, ash is gray, and heated substrates are red. However, color is not always a useful indicator for evidence of heating. Bone that has been subjected to heating can undergo color changes (Shipman, Foster, and Schoeninger 1984; Stiner et al. 2001), but similar color changes, particularly blackening, can be mimicked by mineral staining (Shahack-Gross, Bar-Yosef, and Weiner 1997). Additionally, black-colored organic material may be carbonized; however, humified organic material can also appear black (e.g., Stahlschmidt et al. 2015; Taylor et al. 1998). Similarly, reddened patches of sediment can be caused by heating, but they can also form through natural processes of oxidation (Canti and Linford 2000; Stahlschmidt et al. 2015). Therefore, any field identification of potential evidence for fire must be followed up by laboratory analyses that can either confirm or refute the field observations. Over the past several decades, numerous laboratory techniques and methods have been developed and applied to suspected burned materials from archaeological sites. These techniques, the type of information they provide, and the capacities in which they can be informative about past use of fire are summarized in table 1.

Despite the plethora of techniques that can be successfully employed in the identification of materials subjected to heat in the past, none of the techniques on their own can clearly demonstrate that the source of this heat was directly related to human behavior. Barbetti (1986) suggested that the macroscopic association of burned areas with concentrations of unambiguously cultural material may provide strong but not necessarily conclusive evidence for anthropogenic heating. However, as in the Peru example from the beginning of this paper (fig. 1), natural fires can mimic anthropogenic ones, so that the simple association of demonstrably burned materials with cultural artifacts can be ambiguous at best and misleading at worst. Since 1986, archaeological scientists have heeded Barbetti’s call for the application of new techniques for identifying heated remains in the archaeological record, but the problem of demonstrating human agency in the thermal alteration of archaeological materials remains. More attention must be paid to the deposit or deposits in which burned materials are found.

We believe that the application of geoarchaeological methods is necessary to establish clear links between human behavior and fire in the Paleolithic archaeological record. As geoarchaeologists working at the microscopic scale, we argue here for a research strategy that moves beyond simply associating cultural artifacts with burned remains in the field. Rather, we advocate for the use of high-resolution approaches to the study of burned materials in Paleolithic archaeological sites. These approaches can be broadly grouped under the category of “microarchaeology” (sensu Weiner 2010). But more importantly, we stress the integration of different types of analyses and contextualization of burned materials within macroscopic and microscopic deposits.

**Summary and Concluding Comments**

As seen in the preceding case studies, determining whether one has evidence for human use of fire at a Paleolithic site is more complicated than simply establishing whether burned remains are associated with cultural artifacts. First, one must determine what is suspected to be burned—whether charcoal, ash, burned bone, or heat-altered stone and substrate—is in fact burned. Multiple studies including those at Schöningen (Stahlschmidt et al. 2015) and Zhoukoudian (Goldberg et al. 2001; Weiner et al. 1998) have repeatedly shown that simple field identifications of heated remains are not reliable; laboratory tests are necessary for firmly establishing whether an object has been subjected to heat in the past. Thankfully, numerous techniques have been developed over the past several decades for examining how archaeological materials have been transformed through heating.

On the other hand, when these techniques are used alone, they cannot demonstrate that the agent of heating was human rather than natural (see also Aldieas 2017). One must establish whether the burned materials are located where originally
burned or whether they have been redeposited or transported since combustion. Determining the depositional history of burned materials—along with any other type of material contained within an archaeological site—requires that one conduct a geoarchaeological study that develops a holistic site formation model. A geoarchaeological perspective is necessary because context is more than the association of certain types of materials within a specific layer or site. Rather, context is the entire history of how these objects came to be associated with one another. By establishing the depositional history of burned remains and cultural materials, we can more readily assess the role that humans played in the formation of burned archaeological remains.

To illustrate this point, we can look at two examples from the case studies above. At Schönningen, Stahlschmidt et al. (2015) reported the occurrence of small fragments of charcoal within layers containing cultural remains, namely, wooden spears and butchered bones. If we assume that context is simply a matter of association, then one could conclude that the fragments of charcoal were produced by humans. However, when they applied a microcontextual approach, Stahlschmidt et al. (2015) demonstrated that the fragments of charcoal were likely produced elsewhere as a result of peat fires and were subsequently transported from their original place of combustion and redeposited within the lake sediments. These results strongly suggest that the charcoal fragments were formed by natural fires despite their association with cultural remains. In contrast, at Qesem Cave, Karkanas et al. (2007) and Shahack-Gross et al. (2014) were able to demonstrate that various types of remains—such as ashes, burned bone, and heated soil aggregates—were associated with one another within single lenses. By establishing the association of these burned materials within individual depositional contexts and by investigating the formation processes of the cave, the authors could convincingly argue that such depositional contexts were not natural and were therefore probably anthropogenic.

Recent studies, particularly those conducted at Qesem (Karkanas et al. 2007; Shahack-Gross et al. 2014) show how a microcontextual approach can provide insights into fire-related behavior not readily gained from other types of studies. At Qesem, the researchers presented clear evidence for repeated, habitual use of fire throughout the sequence and for repeated control of fire in the form of a multiphase hearth. These types of observations go a long way in directly testing evolutionary models of hominin interaction with fire. However, they are possible only through a microscopic approach that emphasizes integration and contextualization of multiple analytical techniques.

Despite the promise that the microcontextual approach has shown, we should not see it as a panacea for making the identification and interpretation of fire use in the Paleolithic easy or simple. In fact, applications of the microcontextual approach to sites with potential evidence for early use of fire have shown how complicated the issue can be. As seen in several of the case studies presented above, the results—even when placed within a microcontextual framework—can be either difficult to interpret or ambiguous. For sites like Kebara and Hayonim, the researchers were able to demonstrate that the repeated burning of hearths produced the sedimentary sequence seen at these sites. However, because the calcareous ashes that originally composed these hearths were susceptible to diagenesis, the researchers needed to study the chemical environment of the cave and how this influenced the preservation of ashes. A microcontextual approach here was essential for understanding the complex interplay of depositional and post depositional processes and for establishing repeated use and control of fire by Neandertals in these sites.

The researchers at Wonderwerk (Berna et al. 2012) could demonstrate at a microscopic scale that burned remains were found in association with cultural artifacts. And while they could argue that the burned materials are probably anthropogenic, they were circumspect in their interpretation of the results: an association of burned remains and artifacts may suggest knowledge and possible use of fire, but it does not necessarily imply control or production.

We can now revisit the ambiguous case from the Peruvian Andes presented at the beginning of the paper. We believe we were rightly concerned that if the remains of the bushfires entered into the archaeological record, it may be difficult—if not impossible—to determine whether they were natural or cultural. Certainly, field observations would establish that circular patches of charcoal and ash were associated with cultural remains. Even the location of one of the patches—within the center of the structure—would imply, based solely on association, that it was likely cultural and may even represent a central, domestic hearth. We suggested that given the possibility of stylistically dating the architecture of the house and radiometrically dating the charcoal from the “hearth” one could potentially establish a chronological association of the feature with the architecture. This scenario could still prove problematic if there is an old-wood effect, or if the house had been used for a long period of time. Even these concerns would be moot in a similar situation from a Paleolithic site, where stylistic dating of artifacts covers broad time periods and radiometric dating has large standard errors or is not directly applicable.

However, a microcontextual analysis that would examine the depositional context of the burned remains may help resolve the issue. For example, a micromorphological study may provide evidence for an occupational hiatus between the last use of the structure (such as a floor or concentrated occupational debris) and the burned feature. This evidence could be a thin layer formed from the collapse of the roof of the structure or could include a thin layer of windblown sand, which would only accumulate once the building had been abandoned. Similarly, a micromorphological study may identify increased biological activity directly below the burned feature or even formation of a soil, which would imply stasis in accumulation and probably abandonment of the structure. Although all of these scenarios are hypothetical, they illustrate how an interpreta-
tion of human interaction with fire requires a thorough and detailed understanding of the formation history of an entire site that can only be obtained at the microscopic scale.

Researchers have successfully applied the microcontextual approach to critical sites that are, or have been, often quoted to document the presence of fire in early human history, including Zhoukoudian and Schöningen. Microcontextual analyses have also provided suggestive evidence of fire at sites that were not readily thought to have them at first glance (e.g., Wonderwerk). In this light, it is clear that such multimethod approaches need to be expanded to other sites, particularly early ones when circumstances permit, that have been thought to have evidence of early use of fire (e.g., Swartkrans, Beeches Pit, Chosowanja, Olorgesailie) or other, yet-to-be-discovered sites.

Attempts to study hominin interactions with fire in the past necessarily depend on the context of the objects, features, deposits, and the site in its landscape (see examples in Aldeias 2017; James 1989; Sandgate 2017). So much of the older literature and excavations—and sadly, many current ones as well—fail to document or appreciate deposits, stratigraphy, geoarchaeology, and site formation, so we have a rather eclectic and fuzzy view of fire from ancient and even more recent prehistoric sites. The message for the future seems clear: we have to make a concerted effort to closely examine the context of archaeological deposits at all scales using microcontextual approaches (e.g., micromorphology, μ-FTIR, micro-XRF, μ-XRD). Without such an approach, we can hope to achieve only incomplete results and answers.

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Goldberg, Miller, and Mentzer Recognizing Paleolithic Fire S189


Experimental Approaches to Archaeological Fire Features and Their Behavioral Relevance

by Vera Aldeias

The uses and functions of fire in early human adaptations are commonly debated and at times very controversial topics. It is important to recognize under what circumstances and conditions specific fire-related traces can be produced and preserved in the archaeological record. Currently, a growing body of data is emerging on the application of experimental research to the study of archaeological hearths and their residues. In this review, I draw together aspects of such available experimental data, particularly those pertaining to the sedimentary expression and components produced during simple campfires. I highlight not only what one can find in ideal preservation conditions but also what type of indirect alteration proxies can be expected to survive in the archaeological record. I then discuss the implications of such data for analyzing anthropic fire features, their timing, and their meaning in terms of behavioral complexity in the use and manufacture of fire during the Paleolithic.

1. Introduction

Fire is a key behavioral and technological adaptation in human evolution, and today all modern societies routinely rely on fire. Early fire use by the genus *Homo* may have been a crucial adaptation leading to behavioral traits, such as cooking, extending activity time by providing light, warmth, protection against predators, and as a driving mechanism for technological innovations (Brown et al. 2009; Mazza et al. 2006). Fire use might also have been an important catalyst for the evolution of biological and social traits (Gowlett 2006; Twomey 2013; Wrangham 2006, 2017). It is therefore not surprising that decades of research have focused on the first evidence for fire in the archaeological record (James 1989). A related aspect, and one often less investigated, is when fire actually started to be systematically incorporated in the adaptive tool kit of past humans. This differs from research dealing with first appearance of fire use and focuses on when humans became proficient in making and repeatedly employing fire in their activities. Roebroeks and Villa (2011) suggest that early European hominins did not “habitually” use fire before 400 kya, whereas clear evidence for pyrotechnology exists in later Neanderthal contexts. Conversely, other authors argue that although Neanderthals did use fire, this was not an essential part of their adaptation, and European Neanderthals might not have been obligated fire users (Aldeias et al. 2012; Dibble et al. 2017; Sandgathe et al. 2011a, 2011b). The lack of consensus on both the timing of the first use of fire and its recurrent incorporation into human adaptations largely stems from the inherent difficulty in identifying intentionally used, maintained, and manufactured hearths. There are several confounding aspects, such as natural landscape fires affecting archaeological occupations (Bellomo 1993; Buenger 2003; Gowlett 2017), geological processes producing materials that may be mistaken as combustion residues (Stahlschmidt et al. 2015; Weiner et al. 1998), and issues relating to preservation of the original fire components (Albert, Bamford, and Cabanes 2006; Cabanes, Weiner, and Shahack-Gross 2011; Huisman et al. 2012; March 2013; Stiner et al. 1995). We also lack criteria that would allow us to distinguish the maintenance and manufacture of fire versus its harvesting as a natural landscape resource.

The archaeological visibility of fire residues greatly depends on our ability to identify and interpret combustion remains as pertaining to instances of intentional anthropic fire use. It is, therefore, of utmost importance to recognize under what circumstances and conditions specific fire-related traces can be produced and preserved in the archaeological record. One way to obtain such data is through archaeological experimentation. There is a growing body of data from experimental work dealing with fire features and artifactual thermal alteration.

In this paper I review some of the available experimental data in the framework of Paleolithic contexts, focusing mainly on sedimentary components and signatures and, to a lesser extent, on alterations of artifacts that result from association with fires. First I will focus on what the proxies for fire are. Then I will discuss experimental results for the types of fuel used, the effects of hearth location on artifact alteration, and elements indicating the intact or reworked nature of hearths (fig. 1).
Finally, based on the available data, I discuss the archaeological significance of burned artifacts and inferences for hearth functions. The overall goal is to present a comprehensive though not exhaustive review of the application of experimental research for the understanding of combustion features.

1.1. Fire Proxies and Their Contextual Arrangement

Combustion residues can be broadly divided into direct (primary) and indirect (secondary) evidence. Direct fire residues are the by-products created by burning. The nature of these by-products is intrinsically dependent on the type of fuel used and consists mainly of calcitic ashes, charcoals, siliceous components (phytoliths and siliceous aggregates), calcined bone fragments, or dung calcitic spherulites. A simple campfire can create diagnostic sedimentary signatures expressed as a succession of discrete sedimentary lenses, typically with an uppermost ash-rich lens commonly resting on blackish (often charcoal-rich) deposits in wood-fueled fires. However, if these somewhat fragile sediments are not protected or rapidly bur-

Figure 1. Schematic diagram illustrating the several phases of hearth construction, use, and preservation, with main factors influencing the archaeological expression of such evidence. The numbered circles refer to sections in this paper that deal with the available data from experimental archaeology. A color version of this figure is available online.
ied, they can then be easily displaced or chemically altered and may become essentially invisible in the archaeological record.

Another type of evidence for past fires relates to indirect proxies. These are artifacts or sediments altered because of fire temperatures. Depending on the temperature threshold, such heating can result in important structural and mineralogical transformations (Aldeias et al. 2016a, 2016b; Chu et al. 2008; Elbaum et al. 2003; Maki, Homburg, and Brosowske 2006; Schmidt 2013; Schmidt et al. 2013; Stiner et al. 1995; Toffolo and Boaretto 2014; Weiner et al. 2015). Therefore, thermally altered artifacts (bones, lithics, shells, seeds, etc.) or deposits (soils or sediment aggregates mixed with the original fuel, or the heated substrate over which a fire is built) are relevant indirect proxies for past fires. Diagenesis and taphonomic processes can equally affect burned artifacts and deposits, leading to their displacement and loss of primary position and contextual association (fig. 1). What is important, however, is that several heat-related transformations are irreversible even at a geological timescale. Therefore, diagnostic artifacts (e.g., burned lithics or bones) can have a higher chance of surviving in the archaeological record when compared with the more “fragile” components such as wood ash.

2. The Evidence for Fuel

The type of fuels being burned can result in distinct sedimentary accumulations and are an essential variable for combustion parameters, such as the duration of the fire, management strategies, and associated average and maximum temperatures (fig. 1; table 1). Fuel characteristics can also be relevant indicators of paleoenvironmental aspects (e.g., the type of vegetation cover surrounding a site) as well as higher-level inferences about human behavior in terms of selection criteria, gathering efforts and costs (Henry 2017; March 1992; Théry-Parisot 2002a, 2002b; Théry-Parisot, Chabal, and Chrzaevzez 2010), and efficiency in relation to desired hearth functions (Henry and Théry-Parisot 2014; March 1992; March and Wunsch 2003; Simpson et al. 2003; Théry-Parisot 2002a, 2002b; Théry-Parisot and Henry 2012; Villa, Bon, and Castel 2002). Substantial experimental work has been done in the domain of paleobotany and to a lesser extent with the sedimentary expressions of fuel-related variables. Here I will focus mainly on the latter.

2.1. Wood and Grasses as Fuel Source

Wood, and to a smaller extent grasses or sedges, are commonly used as fuel sources because of their optimal pyrogenic properties. Their combustion by-products dominate the remains found in ancient hearths. Thermal degradation of the organic compounds starts at ~300°C in a chain reaction that is often complex (Braadbaart and Poole 2008; Pereira, Ubeda, and Martin 2012). The composition of plant combustion residues depends on pyrogenic variables (e.g., temperature, fire duration, oxygen availability, environmental factors, etc.) and intrinsic properties of the plant matter that was used (e.g., physiological condition, anatomic section, density, moisture content, size; Berna and Goldberg 2008; Braadbaart and Poole 2008; Braadbaart et al. 2012; Brochier 1983; Etegni and Campbell 1991; March 1992; March et al. 2014; Théry-Parisot 2001; Théry-Parisot, Chabal, and Chrzaevzez 2010; Weiner 2010).

The by-products of combusted plant materials are mainly charcoals and ash. Charcoals result from the carbonization and incomplete charring of wood (Braadbaart and Poole 2008), whereas wood ash comprises the residual inorganic fraction left after organic material degradation. Ash is mainly composed of micritic (<4 µm) calcium carbonate resulting from the alteration of cellular calcium oxalate crystals contained in plant tissues (e.g., Brochier 1996; Canti 2003; Mentzer 2014; Pereira, Ubeda, and Martin 2012). Other residual components are siliceous in nature, namely phytoliths and silica aggregates, as well as inorganic minerals from soil material originally contained or attached to the used fuel source (Albert, Berna, and Goldberg 2012; Canti 1998; Elbaum et al. 2003; Mentzer 2014; Schiegl et al. 1994, 1996; Weiner 2010). This residual acid insoluble fraction was experimentally estimated to be on the order of only 2% by volume or weight of wood ash (Schiegl et al. 1996). Moreover, the proportion of different constituents varies: phytoliths, for instance, occur in greater concentrations in certain portions of a plant (e.g., leaves and bark) and in grasses or sedges than in wooden species (Albert and Cabanes 2007; Piperno et al. 1999; Tsartsidou et al. 2007; Weiner 2010).

In thin section, ash accumulations have very distinct sedimentary characteristics with a calcitic crystallitic groundmass, and it is sometimes possible to isolate individual or articulated pseudomorph crystals of calcium oxalate (Canti 2003; Mentzer 2014; Schiegl et al. 1996). While these pseudomorphs reflect original crystal shapes in the plant tissues, experimental research trying to link charred morphologies to the specific fuel types have been largely unsuccessful (Wattez 1996; Wattez and Courty 1987). Experiments by Simpson et al. (2003) suggest that some distinction between willow and birch woods could be attained by microscopically examining the crystallitic b-fabric of ash pseudomorphs and its clustering in relation to embedded charcoal fragments at combustions below 400°C. Still, further research is needed to confirm such observations.

Relatively few experiments have targeted the burning of grasses or sedges. Miller and Sievers (2012) conducted a series of fires using these types of fuels. Their micromorphological results show the stratigraphically intermixed production of laminated fibrous charcoals and abundant phytoliths, several of which preserve a well-defined anatomical articulation. It is also noteworthy that by burning grasses and sedges, the overwhelming quantity of combustion by-products were phytoliths, with no observed calcitic ash rhombs (Miller and Sievers 2012). There is little experimental data on the sedimentary manifestation of mixed-plant fuel sources, namely, the combined combustion of wood and grasses within hearths. An interesting archaeological case study, followed by experimental research, is described by Meignen, Goldberg, and Bar-Yosef
<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Recorded temperature (°C)</th>
<th>Fire duration</th>
<th>Fire shape/dimensions</th>
<th>Fuel condition (moisture/state)</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>900-1,000</td>
<td>NR</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Stiner et al. 1995</td>
</tr>
<tr>
<td>Wood</td>
<td>995</td>
<td>4 days</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Canti and Linford 2000</td>
</tr>
<tr>
<td>Wood</td>
<td>920</td>
<td>1 day</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Canti and Linford 2000</td>
</tr>
<tr>
<td>Wood</td>
<td>892</td>
<td>4 days</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Canti and Linford 2000</td>
</tr>
<tr>
<td>Wood</td>
<td>855</td>
<td>1 day</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Canti and Linford 2000</td>
</tr>
<tr>
<td>Wood</td>
<td>818</td>
<td>1 day</td>
<td>Open flat fires</td>
<td>NR</td>
<td>Canti and Linford 2000</td>
</tr>
<tr>
<td>Wood</td>
<td>600</td>
<td>1-3 hours</td>
<td>Open flat fires</td>
<td>Wheel-dried (12%-20% moisture)</td>
<td>Bellomo 1993</td>
</tr>
<tr>
<td>Wood (sicklebush)</td>
<td>466, 780</td>
<td>3 hours 45 minutes, 5 hours</td>
<td>Open flat fires (ca. 40 cm diameter)</td>
<td>Wheel-dried (12%-20% moisture)</td>
<td>Bentsen 2013</td>
</tr>
<tr>
<td>Wood (sicklebush)</td>
<td>562, 730</td>
<td>4 hours 15 minutes, 5 hours</td>
<td>Open flat fires (ca. 40 cm diameter)</td>
<td>Wheel-dried (12%-20% moisture)</td>
<td>Bentsen 2013</td>
</tr>
<tr>
<td>Sedge (Cyperus involucratus)</td>
<td>&gt;800</td>
<td>NR</td>
<td>Flat horizontally laid sedges</td>
<td>Sun-dried</td>
<td>Miller and Sievers 2012</td>
</tr>
<tr>
<td>Grass (Themeda triandra and Imparada cylindrica)</td>
<td>225</td>
<td>NR</td>
<td>Flat horizontally laid sedges</td>
<td></td>
<td>Bellomo 1993</td>
</tr>
<tr>
<td>Grass (Setaria plicatilis)</td>
<td>157</td>
<td>NR</td>
<td>Open flat fires (30 cm × 30 cm)</td>
<td>Not fully dry</td>
<td>Miller and Sievers 2012</td>
</tr>
<tr>
<td>Bone (with some wood)</td>
<td>800-900</td>
<td>73–122 minutes</td>
<td>Slightly lowered, cleared surface (60 cm diameter)</td>
<td>Not fully dry</td>
<td>Théry-Parisot et al. 2005</td>
</tr>
<tr>
<td>Bone (with some wood)</td>
<td>425-605</td>
<td>NR</td>
<td>Several (fresh and dry)</td>
<td>Several (fresh and dry)</td>
<td>Théry-Parisot et al. 2005</td>
</tr>
<tr>
<td>Tree stump</td>
<td>250</td>
<td>NR</td>
<td>Air-dried for 1 month</td>
<td>NR</td>
<td>Bellomo 1993</td>
</tr>
<tr>
<td>Peat</td>
<td>800</td>
<td>NR</td>
<td>Air-dried for 1 month</td>
<td>NR</td>
<td>Braadbaart et al. 2012</td>
</tr>
<tr>
<td>Cow dung</td>
<td>800</td>
<td>NR</td>
<td>Air-dried for 1 month</td>
<td>NR</td>
<td>Braadbaart et al. 2012</td>
</tr>
<tr>
<td>Cattle and sheep dung</td>
<td>630</td>
<td>NR</td>
<td>Air-dried for 1 month</td>
<td>NR</td>
<td>Shahack-Gross et al. 2005</td>
</tr>
</tbody>
</table>

Note. It is not uncommon for only the maximum peak temperature to be reported, though such a peak can be very short lived. Increased research on the average amount of heat and its durability might be of interest in many questions dealing with archaeological hearths. NR = not reported.
(2014). This study was conducted in order to clarify the provenience of millimeter-sized reddish rounded soil aggregates embedded in ash layers at the site of Hayonim Cave. The authors observed similar clumps of terra rossa attached to the roots of grasses growing in the soils around the site, and these would turn to similar reddish colorations when exposed to heat. Meignen, Goldberg, and Bar-Yosef (2014) concluded that bushes or small branches were used as additional fuel sources, possibly attesting to expedient gathering practices near to the site.

One important sedimentary expression of fires is the calculation of the expected volume of ash and charcoal produced by combustion events. Ash yield seems to be a function of two main variables: the completeness of the combustion (which can be more efficiently achieved by using dry wood sources and higher temperatures) and the relative amount of insoluble fraction per weight of the original fuel material. This was inferred from several experimental studies. For instance, Schiegel et al. (1996) found that, although normally used in smaller quantities, the burning of bark, cones, and leaves actually produces substantially more ash than the combustion of wood because of their higher content of siliceous aggregates and phytoliths. Ash yield can also vary according to fuel condition, namely, if the fuel source was fresh or naturally dried wood. A twofold increase in ash production was obtained experimentally using naturally dried fuels as compared with green wood (Albert and Cabanes 2007), and this difference is mainly due to the increased water content in green wood. Minor differences in relative ash weight and volume were also reported in the case of different wood species (Schiegl et al. 1996). In limited oxygen conditions and with decreased heating (e.g., with temperatures >300°C, restricted ventilation, or with abrupt interruption of burning phase due to rain), the combustion of organic compounds ends. This results in an increase in solid carbonaceous residues in the form of charcoal in relation to the ash content (e.g., Braadbaart and Poole 2008; March 1992; March et al. 2014). However, as emphasized by Théry-Parisot, Chabal, and Chrzavzez (2010), experimental results on the amount of charcoal produced and its underlying parameters varies greatly between different studies, making it difficult to correlate the expected amount of charcoal to more specific combustion factors or wood selection criteria before burning.

In actualistic fire experiments, the resulting ash layer tends to be fairly thin, with reported maximum thickness rarely above 2 cm (e.g., Bentsen 2012; Mallol et al. 2013a, 2013b; March et al. 2014). Such experimental hearths typically reflect short-duration events, with the combustion lasting for a couple of hours and only rarely for durations of more than one day. It is indeed difficult to test experimentally the effects of hearths that are continuously used over the course of several months—though ethnographic evidence shows that these can produce ash layers more than 20 cm thick (Mallol et al. 2007). In their experiments burning grasses and sedges, Miller and Sievers (2012) observed a dramatic decrease in the volume of the burned material with a loss of up to 98% of the original thickness of fuel during combustion.

These values can give some idea of the minimum quantity of material present in an archaeological site. However, while experimental data tends to show some degree of correlation between amount of fuel and thickness of the final ash layer (March 1992; March et al. 2014), processes such as compression, fragmentation, and postdepositional dissolution can affect calculations of ash thickness and original fuel yield without a clear control for site-specific diagenetic rates in the archaeological record.

2.2. Bone as Fuel Source

Bone can be another fuel resource. Evidence for bone-fueled hearths has been proposed for several Paleolithic sites, mainly in the Upper Paleolithic (Beresford-Jones et al. 2010; Marquer et al. 2010; Schiegel et al. 2003; Théry-Parisot 2002a) and in Middle Paleolithic or Middle Stone Age contexts (Gabucio et al. 2014; see also Cain 2005; Dibble et al. 2009; Morin 2010; Yravedra and Uzquiano 2013).

Because of their relatively high critical heat flux for ignition (around 380°C; Laloy 1981), it seems that bones cannot be used as the sole fuel to start a fire (Théry-Parisot and Costamagno 2005). In experimental studies, a mixture of wood and bone is commonly used, particularly during the initial stages of combustion. The assessment of use of bone as fuel is based on a set of criteria, namely, the high percentage of calcined bone pieces, a higher proportion of bone to charcoal ratio, and intense fragmentation indexes with an abundance of bones in size ranges smaller than 2 cm (Costamagno et al. 2005; Joly and March 2003; Marquer et al. 2010; Mentzer 2009). The size distribution of burned fragments seems to be more a function of intensity of combustion as proposed by Stiner et al. (1995) than minor variations due to initial bone size (Costamagno et al. 2005; Mentzer 2009).

Experimental research shows differences in pyrotechnology of bone fires when compared with simple wood-fueled fires, and it has been proposed that the use of bone fuels can provide certain advantages. Controlled experiments demonstrate that the use of fresh, spongy bones will significantly increase the duration of a combustion event (Costamagno et al. 2005; Mentzer 2009; Théry-Parisot and Costamagno 2005; Théry-Parisot and Costamagno 2005), with a direct positive relationship between the amount of bone used and the longevity of flames in a fire (Théry-Parisot 2002a). This increased efficiency is due to the flammability of fatty components, indicating that complete fresh bones rich in grease content (i.e., spongy bone sections) are substantially more effective combustibles than wood (Théry-Parisot 2002a; Théry-Parisot and Costamagno 2005). As can be seen in table 1, there is not a substantial difference in maximum temperatures achieved with bone instead of wood fuels in experimental fires, with high temperatures of 800°–900°C reached in bone fires as in wood (see also Joly and March 2003).
Conversely, fragmented, dry, and compact bones exhibit quite different pyrogenic properties when they are used as the main fuel source. Although such pieces can more easily be ignited because of their minor water content, experimentation indicates that these are quickly consumed, and fires fueled with fragmented dry bones tend to be of shorter duration and with lower average temperature than those using complete fresh bones (Mentzer 2009; Théry-Parisot and Costamagno 2005). Similarly, Théry-Parisot and Costamagno (2005) demonstrate that the use of compact bones, which are poor in fat content, will not produce combustion durations distinct from those observed in purely wood-fueled fires.

These important though subtle differences in the condition and type of bones used before burning seem to indicate that the advantages of bone fuels are not straightforward. If we could demonstrate their exploitation by past humans, this would in turn indicate an important degree of knowledge about bone pyrogenic properties. Unfortunately, however, combined effects of combustion and taphonomy can confound the visibility of such differences in the archaeological record (e.g., Cain 2005; Joly and March 2003). Original size selection of complete fresh bones might not be detectable after burning. Furthermore, as pointed out by Costamagno et al. (2005), subsequent reuse of the same hearth will entail further fragmentation and calcination of bones from previous events, creating increased confounding evidence. Experiments dealing with heat-induced changes in bone cremation practices have also revealed that it is challenging to infer bone condition (fleshed, green, or dry bones) before burning (Gonçalves et al. 2011). Finally, preservation is an equally important aspect for assessing original bone type selection. Stiner et al. (1995) used agitation and trampling experiments to demonstrate that burned bones are more likely to be reduced to powder by both compaction and trampling when compared with mildly heated or unburned fragments. Calcined bones are the most susceptible to such taphonomic damage (Nicholson 1992), and their macroscopic visibility in the archaeological record might, therefore, be considerably biased.

2.3. Animal Dung, Peat, and Turf as Fuel Sources

The use of other fossil (e.g., coal), animal (herbivore dung), and organo-mineral-based (e.g., peat and turf) fuel sources are known mainly for later prehistoric and historic archaeological periods. Only rarely have instances of such fuel sources been proposed for Paleolithic sites (e.g., Théry et al. 1996), and here I only briefly discuss experimental data comparing these types of fuel sources with wood.

Livestock dung fuels have been investigated in terms of their archaeological evidence and experimentally described (e.g., Braadbaart et al. 2012; Canti 2003; Gur-Arie et al. 2014; Matthews 2010; Shahack-Gross 2011; Shahack-Gross and Finkelstein 2008). The burning of dung produces microscopic sedimentary components that can be readily identified by the presence of calcitic dung spherulites, burned organic plant tissues (which can include ash pseudomorphs), and residual inorganic components (Brochier 1983; Matthews 2010; Shahack-Gross 2011). Gur-Arie et al. (2013) used a ratio of wood ash pseudomorphs to dung spherulites to characterize the predominant use of dung versus wood fuels. Experiments by Simpson et al. (2003) show the differences between the calcitic nature of wood ashes, the organic-rich isotropic composition of dung materials containing calcitic spherulites (in sheep dung), and the rubefied (reddened) material with phytoliths and diatoms obtained from burning peat and turf. Braadbaart et al. (2012) note that peat and cow dung, in particular, result in a higher release of smoke than wood fires.

3. Hearth Location and Its Effect on Artifact Alteration

Thus far we have focused the discussion on fires and their direct combustion residues. However, because of preservation of these fragile residues, it is common to rely on the concentration and dispersion of noncombustible artifacts to infer the presence of fire. In fact, archaeological interpretations of past fires are often solely based on indirect evidence for fire, that is, the thermally altered artifacts found in a site. It is, therefore, important to reconstruct when and how fires affect surrounding artifacts and deposits.

Archaeological visibility of past fire use is influenced by hearth location (fig. 2), namely, if hearths were built in an occupational site or outside it. The latter will entail little or no archaeological visibility, particularly in the case of simple, nonstructured combustion structures such as those commonly associated with Paleolithic contexts.

Several variables relate to the behavioral choice of hearth location within a site, and these in turn affect the type of evidence produced. For instance, we should take into account the preservation bias toward fires built inside the drip line of caves versus fires built outside, the latter being substantially more exposed to taphonomical processes and increased archaeological “invisibility.” The selection of location is also particularly pertinent for its association with notions of occupation duration and spatial organization of the habitat. Emergent organizational patterns in a given archaeological site—namely activities developed around a fire—can be relevant for reconstructing space management and activity areas. In this sense, evidence for stacked hearths (i.e., distinct and vertically superimposed combustion events) has been proposed for several Paleolithic sites, including early fire evidence at Qesem Cave around 400 kya (Barkai et al. 2017; Karkanas et al. 2007; Shahack-Gross et al. 2014) and in later contexts (e.g., Aldeias et al. 2012; Courty et al. 2012; Goldberg et al. 2012; Meignen, Goldberg, and Bar-Yosef 2007; Schiegl et al. 1996). Experimental work on the superimposition of fire events by Mallol et al. (2013b) has noted the difficulty in discerning relighting events over short-term intervals even at a microscale of analysis. Similarly, on the basis of macroscopic observations, Bentsen (2012) reports on multiple superimposed fires not resulting in
larger hearth areas when compared with single combustion events. Such experiments suggest that discernible stacked combustion features will be identified only in situations of either an intentional deposition of material between distinct combustion events or those related to a substantial amount of time elapsed between each fire event (Aldeias et al. 2012; Mallol et al. 2013b).

3.1. Lateral Proximity to Hearths

The degree to which a surface fire affects the surrounding sediments and artifacts depends mainly on two variables: temperatures reached during combustion and, most importantly, the distance to the fire feature itself. Temperatures within the limits of a fire rise substantially during initial combustion with all types of fuels (see table 1), with a rapid spike in temperatures observed within the first few minutes of ignition. Our experiments (Aldeias et al. 2016a) show that temperatures drop dramatically outside the fireplace limits, and this is true for both the surface immediately adjacent to it and laterally buried deposits. Other experimental work has shown that, as expected, substantial thermal alteration is visible in artifacts directly added into an active fire, while those positioned immediately outside the fire’s limits remain largely unaffected (Mallol et al. 2013a, 2013b; Sergant, Crombé, and Perdaen 2006; Wadley 2009). Only small-sized artifacts, namely pot lids, were dispersed farther away, being ejected distances of up to 3 m (Mallol et al. 2013b; Sergant, Crombé, and Perdaen 2006).

These results suggest that the distribution of burned remains are a function of fire area and can mimic the limits and extension of hearths. Therefore, dissociation between burned artifacts and direct evidence for a hearth in any archaeological context may point to a certain degree of artifact movement and reworking. Causes of such dispersion can be either taphonomic displacements (e.g., bioturbation) or behavioral management of combustion residues (e.g., heat treatment of lithics or cleaning of previous residues), as will be further discussed below.

3.2. Vertical Proximity to Hearths

A somewhat more complex issue is to reconstruct how deeply a fire affects underlying substrate and embedded artifacts. Reports on maximum subsurface temperatures beneath a fire vary greatly because of uncontrolled variables and different experimental conditions (Bennett 1999; Campbell et al. 1995; March et al. 2014; Sievers and Wadley 2008; Wadley 2009; Werts and Jahren 2007). In our recent experimentation (Aldeias et al. 2016a), we used a set of controlled parameters to investigate subsurface heat transfer under a wide range of conditions and variables that have archaeological applicability. This experimental work shows that while maximum temperatures and rate of heat transfer depends on a range of factors (substrate type, moisture content, porosity, fire temperature, fire duration, etc.), significant thermal alteration is expected only directly underneath a fire and not to its sides. The diameter of this alteration is a direct function of hearth size; that is, larger fires will effectively alter equally larger subsurface deposits than smaller, restricted features. This study suggests that under a variety of experimental conditions, temperatures around 400°C and as high as 800°C can be reached at shallow depths (2 cm below the surface) and that at 10 cm below a fire, maximum temperatures may range from 85°C to 250°C (Aldeias et al. 2016a). Subsurface temperatures continue to increase well after a fire is extinct, and it is expected that longer fire durations will further increase subsurface exposure to heat. These results are generally in accordance with previous studies.
reporting on subsurface temperatures (Bennett 1999; Bentsen 2013; Campbell et al. 1995; March et al. 2014; Sievers and Wadley 2008; Wadley 2009; Werts and Jahren 2007). Although temperatures consistently decrease with depth independently of substrate material (Aldeias et al. 2016a; Canti and Linford 2000; March et al. 2014), it is interesting that Bellomo (1993) observed that burning of tree stumps might show increased subsurface temperatures linked to the smoldering root system.

In general, experimentally obtained subsurface temperatures suggest that artifact alteration can occur postdepositionally. An important variable is the duration of the fire event. For instance, while in the experimental study by Stiner et al. (1995) calcination levels were never achieved in buried bones, similar experiments carried out by Bennett (1999) showed that longer (48-hour fire durations) did in fact produce black bone alteration at 10 cm of depth and calcined bones at shallower depths. Bennet (1999) further hypothesized that some differentiations might be made in terms of surface alteration of bones indirectly exposed to heat (buried bones) as compared with those directly exposed to fire, with the former exhibiting more uniform surface color alterations associated with minimum fracturing and warping. Other studies have shown the effects of fire duration in the degree of artifact alterations. For instance, Wadley (2009) notes that red ochre might be artificially represented in archaeological contexts as the result of thermal modification of yellow ochre and iron-rich rocks buried under a fire. In her fire experiments, no color alteration was observed in a short-lived fire event (lasting for 1.3 hours with temperatures >250°C), whereas with longer fire duration (temperatures >250°C for 19 hours) all of the buried materials became reddened, even those buried at 10 cm below the surface (Wadley 2009). Given that temperatures commonly reach above 100°C at up to 10 cm in depth (Aldeias et al. 2016a), experimental research suggests that other artifacts—such as organic materials like seeds, fruits, plant litter, grass, and rootlets—can be postdepositionally altered. Similarly, experimental fires by Miller and Sievers (2012) resulted in the carbonization of a layer of sedges buried below 5 cm of sediments (see also Sievers and Wadley 2008). Mallol et al. (2013a) note that in their experimental fires the black layer sharply underlying ash remains is not innately linked to the fire event per se but instead represents the secondary charring of the surface in which the fireplace was built. Similarly, in our experiments we observed the charring of an organic-rich layer buried beneath 2 cm of sand with the development of a thin underlying ruffled lens—a microstratigraphic superimposition that tends to reflect the typical arrangement of a surface fire but that in this case actually represents the postdepositional alteration of previously deposited sediments (Aldeias et al. 2016a).

The presence and extent of postdepositional alterations due to overlying later fires are relevant because any archaeological materials embedded in secondarily altered deposits are temporally and consequently behaviorally unrelated to the fire feature and its use. Accordingly, these materials and sediments should be separated from the direct fire residues during excavations (Mallol et al. 2013a, 2013b), and special attention to the provenience of burned artifacts versus the location of the direct fire residues is required, particularly when using such materials for chronometric dating or inferences about hearth function.

4. Evidence for In Situ versus Reworked Hearths

4.1. The Effects of Hearth Shape

There are a series of diagnostic sedimentary signatures created by a simple horizontal fire, such as a hearth or a campfire. Un-disturbed fires tend to present a microstratigraphy with an uppermost ash-rich lens that may contain occasional charcoal fragments. These deposits can rest on a charcoal-rich layer that in turn overlies thermally altered substrates. This discrete stratigraphic arrangement in well-preserved hearths has been attested experimentally (e.g., Godino et al. 2011; Mallol et al. 2013a, 2013b; March, Ferreri, and Guez 1993; March et al. 2014; Miller et al. 2010; Wadley 2008; Wadley 2009; Werts and Jahren 2007). Although materials for chronometric dating or inferences about hearth function.
derlying. Thermally altered substrates are a good indication that a fire was present in this exact location. Still, the degree and aspect of thermal alteration varies greatly because it is intrinsically dependent on the nature and content of the substrate itself and equally affected by pyrogenic properties, namely, fire temperature and duration. Thus far, the majority of work reporting on fire-substrate alterations tends to concentrate on the direct replication of site-specific archaeological evidence (e.g., Brodard et al. 2015; Mallol et al. 2013a; Miller and Sievers 2012; Sherwood and Chapman 2005). A small number of experiments provide a wider range of factors that allow for in-depth generalizations about the type of modifications expected under certain conditions and, consequently, what such alterations may mean for inferring past pyrogenic conditions.

One of the common thermally induced modifications is the development of a rubeified (i.e., reddening) layer usually related to oxidation of iron-rich minerals. Experimental work by Canti and Linford (2000) produced varied results, with some of the experimental fires showing a 2–3 cm thick rubeified base whereas others showed no macroscopic alteration. These differences were not necessarily a direct function of temperature, because fires registering lower subsurface temperatures actually became reddened while the hottest fires did not. These fires were not built on top of the same type of sediments, with fires on humic topsoil not presenting oxidized bases (Canti and Linford 2000). Similar results were obtained by Bellomo (1993), who also did not observe any rubeification with the burning of several tree stumps on sandy humic soils, though in this case it is unclear whether this can also be related to the lower temperatures reached (a mean maximum of 250°C was recorded). Bellomo further suggests that wood bark may act as a thermal insulator preventing heat transfer to the surrounding soil, a hypothesis that rests largely untested in the case of natural tree stump fires. In any case, these studies suggest that soil organic matter might prevent substantial rubeification.

Not all substrate thermal alteration is in the form of reddened substrates. Other experimental fires show that substrate organic matter has an important role on the formation of black thermally altered zones underlying fire features. March et al. (2014) noted the formation of thick blackish zones underneatfires on humic soils and volcanic or aeolian silts rich in organic matter. The formation of black basal layers was further investigated experimentally by Mallol et al. (2013a), suggesting that these deposits can represent the fire-altered organic-rich surface and are not the result of direct combustion residues (i.e., the common attribution of black layers to charcoal-rich sediments underlying an ash layer).

The nature and components of the substrate logically play an important role in oxidation and associated reddening (i.e., whether there are iron minerals to be oxidized in the first place). March et al. (2014) showed that oxidation dimensions are related to both the temperatures attained and the nature of the substrate, with reddish alteration visible between 300°C and 500°C depending on soil types. In our experimental studies with a variety of sediment types, all sediments presented some degree of rubeification with the exception of heat applied to limestone sand and calcitic ashes (Aldeias et al. 2016a). In both of these cases, there were mineralogical and color changes associated with thermal alteration, but these did not assume the form of a rubeified substrate. In the cases where reddening was observed, the main factors driving its extension were sediment type and, to a lesser extent, mean temperature and combustion duration. The average thickness of the rubeified layer was ~6 cm, with a maximum thickness of 8.5 cm obtained in wet quartz sands heated for a longer duration of 19 hours at ~600°C. Similar to the results of previous researchers (Canti and Linford 2000; March et al. 2014), when organic matter was present in the subsurface, there was a marked decrease of visible alteration compared with examples from the same heating conditions and the same type of sediments but without an organic component; specifically, sediments with organic matter showed only a 3 cm thick rubeified substrate, when compared with a 6 cm thick rubeified layer using the same type of sediments but without organic matter (Aldeias et al. 2016a).

In terms of the relationship between substrate alteration and hearth shape, experimentation has shown that a fire built on a flat surface can produce an underlying semispherical configuration of altered sediments when seen in cross section (Aldeias et al. 2016a). This topography, readily visible in the case of rubeification, is an outcome of the way heat transfer occurs in the subsurface and is not related to the original shape of the hearth. That flat surface fires can have a cuvette-shaped substrate is, therefore, shown through controlled experimentation, actualistic studies (Bellomo 1993), and heat-transfer models (e.g., Brodard et al. 2015; March et al. 2014). These secondarily altered deposits should not be interpreted as intentional hearth construction in a depression.

4.3. The Role of Anthropic Actions

Besides forming combustion residues, humans can also act as agents of erosion and reworking of anthropogenic sediments. Of particular interest is the identification of syndepositional (i.e., after formation and before burial) human interactions with fire residues, as such data can give us information on space use, maintenance activities, and, at times, fire functions. For instance, in our experimental work with hearths used for roasting shellfish, Aldeias et al. (2016b) showed that spreading and dumping of fire residues outside the cooking area was an essential step in the cooking procedures. Such actions resulted in the absence of a microstratigraphy associated with intact hearths, which in this case would not be due to poor preservation of the fire features but because removal of combustion residues was an intentional activity that directly related to hearth use.

Asserting possible functions for human manipulation involves better characterization of the effects of actions such as trampling, scooping, sweeping, and dumping of fire residues. These have also been tested experimentally. Although having
the lowest effects in terms of disturbing the original integrity of the fire features, experiments with trampling produce the most diagnostic sedimentary signatures. Miller et al. (2010) noted that after short episodes of trampling (1 minute duration), the original structure and microstratigraphic organization of the hearths was still discernible in thin section, with the charcoal layer overlying altered substrate. Similar results were obtained by Mallol et al. (2013b) in trampling episodes of much longer duration (over the course of 21 days), where the blurred limits of the original structures were visible macroscopically, though in thin section the uppermost ash component was intrinsically mixed with angular charcoal fragments, subrounded sediment rip ups, and few rounded ash aggregates. The underlying microstratigraphy showed little modification from nontrampled substrates. Both studies suggest that trampling results only in alterations of the uppermost deposits (only a few centimeters thick) with increased sedimentary compaction, microscopic granular structure, abundant in situ crushing of fragile artifacts (e.g., snapped and crushed bones), and the incorporation of burned remains into the underlying sediments (Mallol et al. 2013b; Miller et al. 2010).

Increased sedimentary disturbance was obtained in experiments involving sweeping and dumping of combustion residues. Sweeping produced the accumulation of a heterogeneous mix of deposits with a reworked ash layer embedding fragments of thermally altered substrate and a chaotic mixture of artifacts showing different degrees of burning (Mallol et al. 2013b; Miller et al. 2010). This accumulation rests on top of substrates not affected by heating. Scooping and dumping of fire residues performed by Miller et al. (2010) resulted in somewhat similar deposits, with an open chaotic structure containing burned artifacts and thermally altered sediment aggregates embedded in a matrix of rounded calcitic ashes. Miller et al. (2010) propose a possible distinction in terms of grain-size distribution between sweeping and dumping, with coarser heterogeneous deposits in dumped deposits and finer grain sorting potentially associated with sweeping actions. In general, these experimental results show that combustion accumulations resulting from sweeping and dumping do not preserve the original hearth structure. Instead, the spreading of combusted materials leads to a set of sedimentary characteristics associated with secondary ash dumps that allows for their identification as disturbed, not in situ, accumulations of combustion material in the archaeological record.

4.4. The Effects of Biogenic and Geogenic Processes

Experimentally testing the effects of biogenic and geogenic processes faces the issue of time. It is indeed difficult to test diageneric processes that occur over hundreds and thousands of years in archaeological fire features. Therefore, the overwhelming quantity of data we have on taphonomy and diagenesis deals with individual combustion components and their stability under varied environmental conditions (e.g., Albert and Cabanes 2007; Berna 2010; Berna, Matthews, and Weiner 2004; Berna et al. 2007; Braadbaart and Poole 2008; Cabanes, Weiner, and Shahack-Gross 2011; Cohen-Ofri et al. 2006; Karkanas 2010; Karkanas et al. 2000; Schiegl et al. 1996; Weiner 2010; Weiner, Goldberg, and Bar-Yosef 1993, 2002). From such data, the degree of preservation and taphonomy of combustion-associated sediments can be indirectly assessed, and past geochemical conditions can be inferred.

In terms of the effects of bioturbation, a recent study has specifically dealt with the interaction of some carnivores with hearth features, which can result in the reworking of the combustion structures (Camarós et al., forthcoming). Bears, in particular, were observed to interact and significantly disturb fire residues used for meat cooking by rubbing themselves in the ashes and charcoal, digging holes up to 50 cm in diameter, and displacing stones and bones away from the original hearth location. As a result, the original experimental hearth sediments and stone arrangement were no longer recognizable (Camarós et al., forthcoming).

5. Archaeological Significance

The archaeological significance of fires depends on being able to attest their anthropogenic origin. We need of course to keep in mind that fires are natural processes and a phenomenon that has occurred throughout Earth’s geological history. Ultimately, therefore, reconstructing instances of anthropogenic (human-made) fire cannot rely solely on the nature of the artifacts per se (the aforementioned direct and indirect proxies) but needs to take into consideration their overall contextual association (Goldberg, Miller, and Mentzer 2017). “Context” refers to the entirety of data pertaining to the internal distribution, orientation patterns, and external association of burned sedimentary components. In other words, it embodies the internal structure of combusted residues and their association with adjacent archaeological data. Understanding the contextual framework is relevant for higher behavioral inferences beyond the assessment of whether a material is burned or not and is essential to tease apart whether (1) burned residues are in fact related to anthropogenic activities, (2) the presence or absence of burned residues is due to human behavior, or (3) burned residues are instead associated with natural landscape burning episodes. It is this understanding of the broader context of combustion remains that is indeed fundamental for well-grounded interpretations of past human pyrotechnology.

5.1. Indirect Proxies: Burned, Yes, but When?

Archaeological sites are far from being pristine contexts even under ideal situations of preservation. Therefore, as mentioned above, the identification of traces for fire often relies on the detection and analysis of the burned artifacts that tend to withstand the passage of time better than the more fragile combustion residues. These are the so-called indirect proxies for
fires. Despite their unquestionable relevance, what the research described above does show is that we must distinguish between different types of indirect fire proxies. On one hand, there are materials that are used, consumed, and burned at the same time that a hearth is active. This heating is, therefore, contemporaneous with the fire event and potentially related to hearth function, the type of artifacts present, and the kinds of human activities that took place around the hearth. Moreover, the study of these burned materials can provide a wealth of information about the fire itself because different materials will respond to temperatures in distinct ways.

Again, however, not all burning results from direct contact with a fire, as there might be a considerable elapsed interval of time between artifact manufacture, discard, burial, and post-depositional exposure to heat. For example, a fire built on top of previous occupations has the potential to directly alter underlying deposits and embedded artifacts. In such cases, the thermal alteration may significantly postdate the fire event, and these burned materials are neither temporally nor behaviorally associated with the overlying hearth. This is particularly pertinent in archaeological sites where a thin layer of sediments often denotes several human occupations overlapping each other and represents sedimentary accumulations over hundreds or even thousands of years.

Thus, in order to distinguish between instances of contemporaneous burning from postdepositional alteration, we need to better understand how fires (both anthropic hearths and natural fires) affect the surrounding and especially the underlying deposits under a wide variety of conditions and substrate sediment types. Above all, such interpretations must be based on context, for which detailed characterization of the sedimentary and microstratigraphic association of burned materials is essential. For instance, we can expect the majority of heated artifacts embedded in ashes to be related to the active fires, whereas those retrieved from thermally altered substrates most probably represent older artifacts pertaining to distinct and possibly markedly different types of human occupations. This distinction is important for archaeological interpretations, studies on spatial analyses, and dating of human occupations.

5.2. What Can We Say about Hearth Function?

The array of behaviorally relevant functions of fires (light, warmth, cooking, protection against predators, etc.) is often stated and lies at the core of why fire technology is seen as a major technological advancement in human evolution. It is also, nonetheless, one of the most frustrating and elusive aspects of ancient pyrotechnological research because pinpointing the exact function of a particular Paleolithic combustion feature has proven to be extremely challenging. The reasons for this are varied. On one hand, there is the nature of the direct data we are dealing with; that is, the incompleteness of the archaeological record even in instances where a hearth has been clearly identified. As seen throughout this review, the available artifactual and sedimentary data often lack enough resolution to distinguish between discrete activities that might have occurred above or around a fire. On the other hand, there is also a conceptual issue. Several functions attributed to fires are difficult to test for or are even untestable through archaeological data simply because they leave no sedimentary signature. For instance, light and warmth are automatic outcomes of every fire regardless of whether their production was the intended objective in the first place. Tackling such functions directly might be a frustrating endeavor. However, it might be possible to better discern patterns in the role of fire by comparing the evidence between several sites and resorting to specifically targeted experimentation to build testable research hypotheses. For example, the amount of light produced by one type of fuel compared to another can be tested experimentally (e.g., does bone fuel produce more luminosity than pine wood fires?). In turn, the obtained results might drive expectations that can be verified between different combustion features and distinct sites, attributing a degree of probability that, in this example, light was a likely intended hearth function.

Such intersite comparative analyses (with comparable excavation and recording methodologies) are still fairly infrequent in archaeological research, though substantial efforts for data collection and excavation standardization have been seen in recent years. In order to interpret hearth function, our research questions need to be tailored to the type of data available. Archaeological experimentation is key for assessing such information on what to expect. As graphically illustrated in figure 3, putative hearth uses might be dependent on multiple variables, and these need to be addressed from an interdisciplinary perspective—not just from the study of the burned artifacts themselves but also the sediments embedding them and their contextual arrangement.

6. Final Comments and Future Directions

The identification of anthropic fire use is an important behavioral question both in terms of its first appearance and the
recurrence of its application in human adaptive strategies. Detailed analyses on the content and context of fire residues can provide a wealth of information. Still, we face conceptual and operational issues on how to identify ephemeral or patchy evidence of burning, particularly in older contexts where archaeological visibility and association might be an issue. Equally challenging is the archaeological identification of fire production, that is, being able to start a fire, versus simply its management. Experimental data described above show the sedimentary invisibility of several relevant aspects, namely relighting episodes. This suggests that thus far, we cannot distinguish between fires that were maintained continuously lit from those revived in short intervals of time. Such potential lack of sedimentary evidence has consequences for questions relating to the capacity of past humans (e.g., western European Neanderthals) to manufacture fire (Roebroeks and Villa 2011; Sandgathe et al. 2011a, 2011b). Consequently, questions dealing with the capability of humans to start a fire versus their choice to use or not use fire resources might go undetectable in the archaeological record.

How much fire was present in a given site and what those combustion events suggest in terms of human selection and choices (e.g., fuels, hearth construction, and syndepositional maintenance activities) are both questions that profit from a solid experimental background in order to interpret the complexity of the archaeological evidence. The majority of archaeological experimentation tends to focus on what can happen but not as much on identifying the circumstances under which it does—or did—happen. This distinction is crucial. Many of the data currently available on fire experimentation deal with site-specific objectives, that is, the replication of what is seen in a particular archaeological layer. Such actualistic experiments (also called realistic or replicative experiments) are driven by the goal of seeing whether a certain type of evidence can be manufactured or produced or replicated. While these are indeed important research questions, they tend to bear little applicability for other archaeological settings and contexts. For instance, many experiments use sieved sediments from a particular site to conduct their experimentation. While there might be issues on how analogous such sediments truly are to the actual stratigraphic layer, what is also important is that the obtained results relate to that site alone, entailing little applicability in other contexts. Moreover, many actualistic experiments produce confounding results, and we are left with contradictory, nonreplicable data that are at most anecdotal and difficult to interpret. This is mainly due to the lack of control on certain variables during experimentation.

Fortunately, in recent years, we have increasingly seen research applying more tightly controlled experimentation. By limiting the number of variables, both in laboratory and field conditions, we have progressively gained a clearer picture of relevant factors in the formation and integrity of fire residues. For a long time, any blackened or reddened sediments or artifacts were commonly—and often wrongly—interpreted as hearths, whereas currently we understand that an array of techniques can be used to closely investigate whether a material was burned, the degree of its alteration, and its microcontextual association. Moreover, an important development is the close integration that archaeological-driven experimentation has had with other disciplines, for example, borrowing analytical techniques from the earth sciences, chemistry, and biology. A growing line of research applies microcontextual approaches instead of averaging out the sedimentary debris from fire features. Such innovative methodologies are promising research avenues for the analyses of particular sedimentary components that until recently had remained virtually invisible.

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Cave (Cantabria, Northern Spain): deliberate use for fuel or systematic dis-
Evidence of Burning from Bushfires in Southern and East Africa and Its Relevance to Hominin Evolution

by J. A. J. Gowlett, J. S. Brink, Adam Caris, Sally Hoare, and S. M. Rucina

Early human fire use is of great scientific interest, but little comparative work has been undertaken across the ecological settings in which natural fire occurs or on the taphonomy of fire and circumstances in which natural and human-controlled fire could be confused. We present here results of experiments carried out with fire fronts from grass- and bushland in South and East Africa. Our work illustrates that in these circumstances hominins would have been able to walk with and exploit fires, and we emphasize that there can be different levels of fire use. The results also indicate that traditional assumptions about the discrimination of these are not reliable. Grass fires pass through the landscape rapidly in burns of less than 5 minutes duration, but areas of denser vegetation burn to much higher temperatures and for much longer. Trees are also caught in fires and may burn back into their roots, baking sediments. Animal bones on the surface can also become burned, so that presence of burned bone has to be used with care as an indicator of human activity. Duration of burning, repeated nature of burning, and copresence of features of human activity may give a better indication of human involvement.

Studies of early fire have come to the fore in recent years with important discoveries of new archaeological evidence at sites in Africa and other parts of the Old World and new hypotheses about its evolutionary role (e.g., Berna et al. 2012; Gowlett 2010, 2016; Parker et al. 2016; Wrangham 2009, 2017) and significance in the biosphere (Archibald, Staver, and Levin 2010; Scott et al. 2016). The subject of the human role remains controversial because evidence of most burning disappears very rapidly, and there are also possibilities of confusion between evidence of controlled fire and evidence of wildfire. An understanding of early human fire use can be obtained from a number of sources, including physiological and genetic sources (evidence based on metabolism, digestion, or genetics is inevitably largely indirect), but the archaeological evidence has the potential to be the most direct providing that there is an adequate framework for interpreting it (cf. Sandgathe 2017).

Exploration of the issues of early fire use demands the availability of a set of “actualistic” comparative material, which remains largely lacking despite important pioneering efforts (e.g., Bellomo 1993, 1994; the first fire ethology appears to be owed to Al-Jahiz in the eighth century AD; see Stott 2012). The scope of such work needs to be expanded now, partly because of the great variety of ecological circumstances in which fire occurs and partly because of poor understanding of when fire evidence is likely to be preserved or to decay. Here we present the results of observations and experiments concerned with African bushfires that make available new information about burning temperatures and durations and about effects on bone. We emphasize that this is a field study, not a laboratory study. Considerable efforts had to be made to control the fires and to
ensure that they ran across the target areas where measurement probes had been inserted.

Previous Research

Evidence of patterns and consequences of burning have been presented a number of times (e.g., Alperson-Afi and Goren-Inbar 2010; Bliege Bird et al. 2012; Bond and Keeley 2005; Davies, Holdaway, and Fanning 2016; Griffin 2002; Perlès 1977; Sergant, Crombe, and Perdaen 2006; Scott 2000, 2009; Vale 2002; see also Alperson-Afi 2017; Barkai et al. 2017; Dibble et al. 2017; Henry 2017; Holdaway, Davies, and Fanning 2017; White et al. 2017). Bellomo’s work (1993, 1994) remains one of the most general treatments of methodology, based on a number of experimental studies as well as literature and aimed to give documentation to the main kinds of natural fire as well as to the nature of hearths.

Bellomo’s research was geared to discriminating human fire from natural fire. Like many authors, Bellomo was inclined to emphasize temperature as a discriminator. He also suggested that grass fires reached high temperatures only for a very short period (cf. Clements 2010) and therefore do not create any considerable burning of materials. He set out criteria for recognizing hearths. He believed that they could be discriminated from natural bole fires, regarding the latter as rare. In his experiments Bellomo found it difficult to generate tree stump fires, and he tended to minimize their role although they can occur at times even in rainforest environments (Tutin, White, and Mackangamissandzou 1996).

Some assumptions drawn from Bellomo’s work are widespread, most especially that temperature is useful for discrimination of hearth fire and wildfire. The presence of burned bone, although not much used by Bellomo, is frequently also taken as an indicator of human activity (e.g., Bosinski 2006; Brain 2005; Brain and Sillen 1988). Again, further testing of the issues would be highly desirable, and what we report in this paper takes steps in that direction.

Pattern of Experimental Fire Research

We report here on recent experiments and observations in South Africa and East Africa. They cover (1) experiments in burning set up as part of landscape management at Florisbad Quaternary Research Station, (2) following a bushfire and study of traces of previous bushfires at Soetdoring Nature Reserve near Florisbad, and (3) observation of very recent bushfires and charcoal burning at Kilombe farm in Kenya together with the recording of temperature variations with depth in experimental campfires.

In this work it was possible to compare some burning events as they happened with the results of other fires that had occurred recently nearby. In this respect the pattern is similar to that in Robbins’s classic study of the decay of Turkana huts, where he was able to compare some as they were abandoned with others that were in the process of collapse (Robbins 1973). Ideally one would follow a complete cycle of burning, decay of organic remains, and vegetation recovery, but this would involve great expense, and in any case some useful observations are the result of purely chance factors (e.g., encounter of a fire on a given day).

The research addressed three particular questions. (1) To what extent do the temperatures observed in grass fires and brush fires match those commonly accepted in archaeological observations and interpretations? (2) To what extent do tree fires occur, and to what extent are the traces left by these able to mimic hearths? (3) To what extent do grass fires and bushfires affect surface bones?

The Fires: Outline

Most of our observations were made around Florisbad, about 40 km north of Bloemfontein in South Africa (fig. 1), where a reserve extends to the north of the museum (fig. 2). This research was stimulated by observation of an accidentally started bushfire close to the museum in 2008 and also by similar encounters with fires at Kilombe in Kenya, possibly inadvertently started by charcoal burners. The range burning at Florisbad, however, takes place as a means toward restoring native vegetation and improving grazing resources rather than for the...
research. In total we were able to observe fire in grassland, in low scrub, and in savanna (or riparian woodland), including groups of trees of up to about 5–8 m in height. We were able to determine effects on vegetation and also on organic materials such as bone. In general, wind speeds were relatively low at a few miles per hour.

In all cases fire fronts moved through relatively fast, with most immediate burning taking place within a space of a few minutes and of less than 30 minutes even in the case of trees (figs. 3–6 below). Temperatures, however, were exceedingly variable according to type and density of burned plant material, as demonstrated by measurements taken with thermocouples attached to long heat-resistant leads (cf. Govender, Trollope, and Van Willgen 2006).\(^1\)

1. Temperatures were measured with the use of long thermocouples. The tip lengths of ca. 100 cm were heat resistant up to 1,100\(^\circ\)C. The remaining lengths of ca. 12 m could withstand 300\(^\circ\)C and were therefore buried at a shallow depth. Data were logged on a standard temperature recorder from a fire lane either at intervals or continuously recorded with the aid of a video camera.

Fires at Florisbad Quaternary Research Centre and Museum

The museum is set within a region of grassland and small karroid shrubs (sweet veld) with occasional trees, especially closer to water (see Janecke and du Preez 2005). Locally, an area approaching 100 hectares had been farmed historically but has been museum land since 1980. Bush and scrub clearing by fire was organized in this area by the National Museum in 2012 and 2013. The aim of current conservation is to remedy the effects of overgrazing during past farm use and to restore grassland veld vegetation that can support an antelope population. The land is situated at about 1,250 m asl and descends gently to the north toward the Soutpan depression (Kuman, Inbar, and Clarke 1999; Scott and Brink 1992; fig. 2).

In the course of the systematic burns at Florisbad, it was possible to measure burning temperatures near vegetation using thermocouples (see n. 1). Additionally, we were able to place partial carcasses of two antelope for study of burning effects, discussed below.

The burns took place over a number of days in September 2012 and 2013 toward the end of winter and before the onset of any rains. Around the world records show that many lightning-induced fires occur at the start of rains following a dry season (e.g., Gisbourne 1931; Johnson 1992). In all cases here the vegetation was in much the state of dryness that would come into contact with the first thunderstorms a few weeks later. Examples of the burning are described and explained below.

Temperatures of Burning in Open Grassland

Grass burns were conducted on a number of days when wind speeds were relatively low (burns were not permitted when wind speeds were higher than about 16 kph). The grassland at Florisbad is made up of a variety of species similar to those

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**Figure 2.** Museum reserve area at Florisbad. The grassland extends from the museum at the southern end to the edge of the Soutpan at the north (satellite imagery courtesy of Google Earth). A color version of this figure is available online.

**Figure 3.** Temperature measurements of two fire fronts in grassland (veld) at Florisbad.
at nearby Soetdoring (Janeke and du Preez 2005), sometimes occurring in dense stands, sometimes patchy. At Florisbad vegetation/grass height is generally 30–60 cm. The grasses were ignited easily and burned in moving fronts.

Figure 3 illustrates measurements from two adjacent probes in open grassland. In one of these temperature rapidly rose from ambient to more than 500°C, but in 2 minutes it had fallen back sharply toward ambient (i.e., 20–30°C). The other probe records a lower peak (possibly because the highest temperature endured for just a few seconds), but temperature of 120°C was recorded for 4 minutes. Two measurements made on Thelmeda triandra (red grass) the following day in similar conditions indicate a similar picture with peak temperature reached and falling right back within 3 minutes (fig. 4; see also fig. S1; figs. S1–S8 available online).

Temperatures of Burning: Small Shrubs and Grasses

This example from the same suite of fires demonstrates temperatures and speed of burning in grassland in relation to a small shrub (GPS point 358: 28 45.159S/26 05.974E; September 17, 2012): small karroid shrubs occur patchily in the area (Janecke and du Preez 2005) and may significantly affect intensity of burning. Four thermocouples were set on a bush at heights of 60 cm and 10 cm, on an adjacent small stump at a height of 25 cm, and in grassy brush at 5 cm. At 9:45 a.m. ambient temperatures on these were 18°–24°C. Fire was set locally at 10:03 a.m. As the front hit the area around 10:05 a.m., temperatures rose to 151°C, 240°C, 40°C, and 183°C respectively. All temperatures then sharply declined except that of the grass brush, where the temperature rose briefly to 500°C. By 10:30 a.m., temperatures had fallen to 43°C, 39°C, 27°C, and 25°C, closing toward the original ambient temperatures. A piece of cattle dung 2 m from the bush was recorded burning at 605°C at 10:16 a.m. and at 1,045°C at 10:37 a.m. Figure 5 illustrates temperatures in an additional similar case of bush and grass burning.

Another case illustrates the way in which the initial rapid burn can lead to continued burning and higher temperatures in localized areas of denser vegetation (fig. 6). One probe was attached to a small prickly bush, another to densely matted grass. The bush burned fiercely and rapidly without very high temperature, but temperatures of the burning grass rose to almost 600°C and were maintained at greater than 200°C for around 15 minutes. Most interesting, adjacent dung was ignited, but it did not burn rapidly; rather, the temperature was rising toward 50°C as the others declined, and it had the effect of prolonging local burning to at least 30 minutes. In this case the longer burning may reflect input of oily material from the bush coupled with the dense matting of the grass. Figures 4 and 5 also show a slight bounce back of temperature, possibly because woody material took longer to ignite and burn than the grasses.

The principal finding is that although most grass fires had a predictably rapid burning plume structure, time duration, and temperature profile (cf. Clements 2010), in practice wide ranges of temperature variation were observed. Grass fires were of the order of 300°C, but the plume spike rose to about 700°C as gases ignited (cf. Clements 2010). The temperature and duration of burning were notably raised when the fire caught hold of shrubs.

Fires at Soetdoring Nature Reserve

Soetdoring lies about 5 km south of Florisbad. Observations from three bushfires at Soetdoring provided further evidence about burning of vegetation, especially trees, and also of bone. The game reserve flanks a reservoir extending behind the Kruegersdrift dam on the Modder River and lies 40 km north of Bloemfontein and about 5 km from the Florisbad museum.
The landscape is to the eye a mosaic of grassland and savanna, and in botanic terms it is part of the Grassland Biome of the sweet veld and similarly regarded as a mosaic dominated either by grasses or by dwarf karroid shrubs (such as *Chrysocoma ciliata*, *Pentzia incana*, *Pentzia globosa*, and *Rosenia humilis*; Janecke and du Preez 2005). Larger trees are found toward the river, including especially sweet thorn (soetdoring), a species of *Acacia*.

We were able to observe and investigate evidence from three bushfires: (1) a fire in progress on Sunday, September 23, 2012; (2) a fire of July/August 2012, about 6 weeks old at the time of observation; and (3) a fire of Monday, September 10, 2012, observed at the end of the burn and through the following week. The approximate extents of the burns are shown in figure 7. The cause of ignition of fire 3 was reported to be a barbecue fire. Fires 1 and 2 may also have been caused by human activities, such as the dropping of a cigarette. We discuss the fires out of chronological order so as to follow a train of argument.

**Fire 1: Bushfire Followed in Action**

This fire was observed by chance at the reserve on Sunday September 23, 2012. It was immediately visible from about 2 km as it began to consume trees (fig. S2). The cause of ignition is not known, but there did not appear to be any visitors in that area of the park. We were able to follow the fire for more than 500 m, up to the point where it came up to a creek, which it eventually passed around.

It was striking that the fire very rapidly consumed trees (fig. S3), moving rapidly and loudly, but also that the burning...
was selective, with adjacent trees and even grass patches often unaffected. We were able to observe the way in which trunks burned through at the height of 1–1.5 m and in which the upper parts of trees were often entirely consumed so that nothing remained except fine ash within a few minutes.

In general, the fire burned out by the water’s edge, but in places it consumed reed beds, with dramatic flaming and smoke. We were not able to use temperature probes but inferred that there was a great range of burning temperatures even very locally.

Fire 2: Trees and Associated Debris Left by Fire

This fire, the earliest of the three, was not observed by us; it must have been similar in character to fire 3 but perhaps hotter, judging by the damage, and more extensive (fig. 7). An area was recorded about 700 m south of the believed fire source at (28 49.693S/26 03.088E). Here the fire had passed through a group of trees forming a sparse copse about 25 m across, and two areas of 15 × 9 m were plotted (fig. S3).

The burning illustrated several features characteristic of the area. The trees had burned to a varied degree. One stump indicated a cut by flames at about 1.5 m (fig. S4). At least two or three trees had been consumed entirely, with only fine ash trails preserving the pattern of the fallen trunks and branches.

In several instances the trees had burned right back into their roots, creating fire-baked zones up to 2 m across (figs. S5, S6). These are of particular interest in the sense that they could mimic hearths and create clasts of baked clay possibly similar to those found at Chesowanja (Gowlett et al. 1981). We excavated a section across one of these combustion zones and found that the baked zone extended to about 20 cm deep (fig. S6), almost certainly indicating high temperature maintained for considerable time (we discuss hearth temperatures further below in relation to experiments at Kilombe). In general, from inspection of quite a number of such burned out stumps, we observe that they could be distinguishable from hearths if they preserve the shape of spreading descending roots (a criterion also noted by Bellomo 1993). Even where there is a wide-open depression, the roots can be observed at the margins, sometimes with charred wood preserved (note that Melson and Potts [2002] described other ways in which natural baking of sediments can occur in East African environments).

Last, there were scattered bones on the surface by the trees of a duiker-size bovid. The scapula and humerus were quite heavily burned, suggesting that the brush had burned quite intensely around them.

Fire 3: Bushfire and Effects on Animal Carcasses

This fire, close to the main entrance of Soetdoring Park, we were able to observe while some areas were still smouldering. It gave the best opportunities to study effects on the bones of carcasses. These were of animals that had died and decayed down to their skeletons before the fire, perhaps by a year or more. In each case these had been lying in grass, and there is no doubt from the taphonomic indications discussed below that the animals had already been dead for at least several months and their soft parts were fully decomposed at the time that the fire passed.

**Bones of medium-size bovid (hartbeest Alcelaphus buse-**

The skeleton was essentially complete, with the bones scattered across an axis of about 4 m and bone positions partly representing past anatomical connections. Bones were variably burned, with the skull and horn cores having suffered particularly, perhaps because they stood a few centimeters higher above the surface than the other bones. The skull is the most burned (fig. S7), and it is separated into two pieces. Nasal passages were the focus of burning (the main part of the cranium had been lying on its base, with the frontal uppermost). In contrast, the hemimandibles were scarcely burned except for the tip of the condyles on both sides. The scapulae had lain flat on the ground: one was charred brown on the dorsal surface, the other just on the dorsal spine. Both sides of the pelvis are quite strongly charred, especially around the pubic area, but also around the margins of the ilia (fig. S8).

On the limb bones there was very little sign of burning except light charring around the distal right humerus, probably after the epiphysis had detached (the equivalent epiphysis was in position on the other side, with no obvious burning). The ribs showed little sign of burning, except at vertebral ends, where there was some charring.

Charring of the vertebrae is very variable, prominent in some pieces, absent in others, but the place of burning varies between equivalent vertebrae. Dorsal spines were most commonly charred.

**Jackal (Canis mesomelas).** The jackal had apparently become ensnared at the foot of an old wire fence, probably no more than a few months previously, as some of its pelt remained as a mass. Its skeleton is virtually complete; again, its bones were variably burned. Some show little or no trace of burning, but others, including the flat plates of vertebral spines, are considerably charred. The skull/mandible has slight charring around the nasal aperture. The cervical vertebrae show charring of spines, above or below, and one more than the others. The thoracic vertebrae have the heaviest burning on the spines (six badly charred vs. five scarcely charred). The lumbar vertebrae have minor burning to the spines. The pelvis has some charring to the margin of the ilium on one side. About half of the ribs are charred at one end, usually the proximal end. And the upper and lower limbs have very little visible damage, with just slight charring to the ridge of one scapula. The foot bones, metapodials still articulated, are uncharred.

**Small antelope.** The small duiker was about 70% complete: one forelimb had vanished, and two feet were missing, as was most of the thoracic vertebrae. The ribs were fragmented. Fire damage was as follows. The skull has light charring of the edges
of nasal cavity. The mandibles show light charring of the tip of one condyle. On the cervical vertebrae, there is darkening at the tip of one spine. One complete thoracic vertebrae is lightly browned. Of the lumbar vertebrae, five articulating, there is plain charring of dorsal spines and very light charring of lateral spine tips. The forelimb shows taphonomic damage to the plate of the scapula and charring of the chewed edge and on the ridge. There is none to the cup. The distal end of the humerus is missing, and there are signs of light chewing; the sharp bone edge is considerably charred. The proximal end of the radio-ulna is considerably charred, and the radius is fragmented and charred on one edge. The ilia of the pelvis had separated, and there is light chewing of the tips and edges and light charring of the pubic area. There is light charring to parts of both femurs (also taphonomic damage from chewing), one tibia, and one calcaneum. There is no obvious burning damage to the foot parts preserved.

Experimental Burning of Antelope Carcasses at Florisbad

We set out to determine whether fresh antelope carcasses would become burned in a comparable way in terms of visible damage to bones and whether the presence of meat would affect the burning. To this end, two culled carcasses, a black wildebeest and a blesbok, were acquired from the Caledon Nature Reserve (a reserve managed by the Free State Provincial Government).

Black Wildebeest

This was a young adult black wildebeest male with the third molar erupted but not yet in wear. The carcass was complete but skinned and with the intestines removed. At Florisbad we detached the carcass, except for the right front limb, which was detached and kept separately.

Blesbok

This was an adult female blesbok with a broken left metacarpal that was incompletely healed. (The break must have occurred a few seasons ago, because there was much additional bone growth around the break, which forms in an attempt to stabilize the bone. From the pelvis it is clear that she had had several calves.) The carcass was received intact, with skin still on but with the intestines removed. The carcass was kept as it was.

We wanted to see the effect of the grass (veld) fire on (1) defleshed bone (the carcass of the black wildebeest without the right front limb), (2) bone with flesh on but without skin (the right front limb of the black wildebeest), and (3) bone with flesh and skin on (the carcass of the blesbok). Therefore, we put out the defleshed black wildebeest carcass, the right front limb with flesh still on, and the blesbok carcass with flesh and skin on. These parts were left in the path of the fire so that the fire could run over them, as if in a natural fire.

Temperature probes were attached to the limbs of the blesbok and to the wildebeest limb. In an effort to maximize burning, the specimens were set beside a fairly large bush (otherwise the situation was as in the other grass fires described). Figure 8 shows the resultant temperature profile and burning duration.

The two curves suggest that the temperature for one thermocouple was maximized by being in the plume of burning, the other minimized perhaps by being on the top of the carcass and not exposed to direct flame. They do, however, have similar profiles, showing the usual rapid heating with the fire front followed by a cooling off of about 10–15 minutes.

When inspected, the blesbok skeleton, which had meat and skin attached, showed very few signs of burning. These were confined largely to lower parts of limbs. The left scapula spine was darkened; the lower part of the left front limb was darkened (distal shaft of metacarpal) or had became white or gray and brittle (phalanges). Tibia and metatarsals of the left hind limb also became white and brittle. The right front limb of the black wildebeest, with its flesh but no skin, showed only a slight darkening to the proximal lateral part of the radio-ulna. In summary, we found that in the passing fire the meat attached to the blesbok and to the right limb of the wildebeest did not heat sufficiently to cook substantially and that it served to protect the bones.

The rest of the skeleton of the wildebeest, which was defleshed and placed in a separate fire path, could have been more directly exposed to burning because of the defleshing, but in fact there were very few signs of burning other than slight darkening here and there. The blades of the ilia were slightly darkened and brittle. As with the blesbok, the tibiae were affected, with the left in particular being brittle and crumbly.

Figure 8. Temperature measurements of wildebeest and blesbok limb bones in grass fire and bushfire at Florisbad.
Experimental Campfires at Kilombe, Kenya

Experimental fires were carried out by Sally Hoare on clay rich substrates in the area of the archaeological site of Kilombe, Kenya (Gowlett et al. 2015), and the aim was to provide a further check on the common statement that campfires burn in the range of 300°C–800°C (e.g., Bellomo 1993, 1994 as previously cited; also Gowlett et al. 1981). On the first day, the ground was prepared by removing the first 5 cm of soil and then marking out an area of 150 cm by 150 cm. K-type thermocouples were used in order to take temperature readings at regular intervals of 15 minutes during burning over a period of 1 hour 30 minutes. This procedure was repeated for a further campfire on the second day. The thermocouples (T) were arranged in two rows, one in the center of the fire and the second on the periphery of the fire and at the different depths of 1–2 cm (T2), 3–4 cm (T3), and 6–7 cm (T4). A further thermocouple was used to record the temperature of the actual flames during burning (T1); that is, it was lodged above the fire. The fuel used was local wood, chiefly Acacia.

The highest temperatures were recorded by thermocouples T1 and T2, which were recording the temperatures of the actual flames and at 1–2 cm depth, respectively. Maximum values for T1 varied between 480°C and 620°C, and T2 varied between 380°C and 402°C. Temperatures recorded at depth were much lower and did not exceed maximum temperatures of 248°C at 3–4 cm (thermocouple T3) and 150°C at 6–7 cm (thermocouple T4). Thermocouples T5–T7, placed at the periphery of the campfire, did not record temperatures above 58°C. Temperatures were similar for the second 90-minute fire the following day.

These temperatures clearly occupy a similar range to those of the passing grass fires. The suggestion that temperatures of hearths and campfires can range from 300°C to 800°C is likely to be accurate in relation to the flames but not necessarily in terms of the firing temperature of the underlying soils and sediments, a point that may have implications for the use of temperature measurements to identify human activity in the archaeological record. Much lower temperatures than are generally attributed to human campfires were recorded during the experimental campfires at Kilombe, specifically at depths of 3–4 cm, although at a depth of 1–2 cm temperatures just over 400°C were recorded. This may in part be due to the relatively short burning times of the particular experiments. (The fire fronts described above also often passed without consuming much of the lowest level of grass and dry plant debris, suggesting that there would be little if any effect on the underlying sediments.) In other camp fires we have seen considerable baking of sediments, which did not occur here, suggesting that longer duration experiments and also variations in fire size are needed for establishing a range of comparisons. There is an issue of preservation, as complete deposits rarely survive on early hominin sites, so traces of a temperature gradient could easily be lost. The figures again suggest that temperature on its own is not a reliable indicator for discriminating between human-controlled and natural fire but also emphasize that various factors influence the degree of baking of sediments.

Discussion

The fire experiments detailed here bring together a number of points that may sometimes be common knowledge in forest fire studies (e.g., papers in Scott et al. 2016) but that have not been established or applied in strict archaeological terms. We have concentrated here on documentation of the visible taphonomy of fire remains rather than on behavioral interpretations. The experiments were often carried out as ancillary activities to range management or other research and clearly mark only a beginning to work of this kind. They were carried out in the open veld in the context of fire hazards, and considerable efforts had to be made to ensure that the fires passed over the target thermocouples and to keep the fires within control. Our efforts therefore concentrated on establishing temperatures and rates of burning. As we took the opportunities presented by chance factors, such as the ongoing accidental fires at Soetdoring, we were not always able to have prior choice of the experimental materials. We do not know exactly how long bone distributions had lain on the surface or how much the collagen in the bones had decayed. With temperatures and durations of burning established, however, such factors can be much more easily studied in experimental situations that do not involve bushfires but that rather make use of smaller fixed experimental fires or even ovens. Similar observations can be made about the burning of sediments. We believe that most campfires, like those at Kilombe, do not generate a great deal of heat below and do not bake sediments to any depth. The passing bushfires also often have little effect on the lowest vegetation and plant roots. On the other hand, tree burns generate great heat and can bake sediments through 20 cm or more. Continuing controlled work on the burning of sediments is clearly valuable for establishing a broader picture (Aldeias 2017).

At the level of animal behavior, it is plain that for all its great importance fire does not create resources, rather it converts or attracts resources. The fires studied in South Africa were set in a low resource area, and although there were signs of effects on rare invertebrates, birds, and small animals such as tortoises, all of which would be of interest to hunter-gatherers, these were very infrequent in these particular landscapes. In another environment, hominins might find that the density of resources would give far higher incentives for following fire. As far back as the ninth century AD, Al-Jahiz commented on the large numbers of animal species attracted to a fire (Stott 2012). In the fires observed by us, the combination of relatively low vegetation fuel load and low wind speeds allowed safe transit for humans around the fire areas, as has also been observed for chimps in West African savanna (Pruetz and Herzog 2017; Pruetz and LaDuke 2010), but the greater intensity of the burn at Soetdoring on Sep-
t ember 23 dramatically highlighted the power of fire and particularly its ability to destroy trees very rapidly.

Stump fires are of particular interest here as they were generated with difficulty in Bellomo’s (1993, 1994) work and feature little in his scheme but could potentially lead to creation of hearth-like features. It is therefore useful that we observed evidence of stump fires numerous times in the Soetdoring fires. In the African savannas many trees are fire resistant, and we have rarely observed evidence of stump fires such as presented here, although evidence of tree stump fires has been observed at Chesowanja in Kenya, where a wooded area was destroyed in the 1930s (Clark and Harris 1985) and charred stumps were still visible in recent years.

We observed baked clay evidence, similar to that observed in the Soetdoring fires, in Kenya when a bushfire took place in January 2011, progressing from the northeast to the southwest across large parts of Kilombe farm. Our group narrowly missed observing the fire but was able to search its consequential evidence some months later in July 2011. One burned stump recorded by us at Kilombe appears (from oral evidence and inspection) to have been a dead tree with its core already rotted away. Sometimes these are found at the heart of a termite mound that has built up around the tree, and in that case baked clay would also be produced in a burn. Most of the trees burned at Soetdoring, however, were certainly alive.

At Soetdoring there was a common scenario of a fire plume from grass and shrub fire that, as it passed, would attack the tree boles at a height of around 1.5 m. They would then burn through at this point, with the upper part dropping on its base (figs. S3, S4); both parts would then continue to burn, the stump downward into its roots and the upper part outward toward its extremities, which sometimes remained unburned. The obvious archaeological relevance is that such fires burn hot, certainly up to 800°C—the full range of hearth fires—and that they can also create baked areas.

Although this evidence seems a cautionary tale—that natural tree fires may cause hearth-size baked features—it is encouraging that they also corroborated an observation of Bellomo (1993) that the shape of the tree root features is distinctive and could be distinguishable from a hearth. As indicated in figures S5 and S6, the spreading roots directed the shape of the combustion feature produced.

At Soetdoring, Adam Caris located one such tree burn shortly after the fire. Ash filled the hollow in the baked clay. Not only did it have a temperature of around 400°C, this was maintained for several days afterward. It suggests the possibility that in the early days of interactions with fire, hominins could easily have been drawn to any feature that naturally retained a high temperature for a long period.

The studies we report here can be related to early human behavior and the likelihood of its preservation in a number of ways. Chance factors ought to be emphasized both in the primary creation of a record and its later preservation. It seems likely that in most circumstances the great majority of hearths will be eroded away through a period of time, generally passing.

Conclusions

The field experiments around Florisbad and at Kilombe emphasize a number of points on a landscape scale and in relation to detailed archaeological evidence. A first point is the great visibility of bushfires and that they can often be followed on the ground with reasonable safety. They attract attention and can signify the possibility that food resources will be available.

Next, temperature is in no sense a reliable discriminator between grass fires and humanly managed fires. Both clearly range through 200°C–800°C on a regular basis.

Baked clay is created by stump fires, by falling burning trunks, and by human activities. The natural instances as observed by us result from intense combustion of tree wood. These instances should have the character—for instance, in magnetic studies—of a single high-temperature peak followed by very gradual cooling. Any trace of repeated episodes of heating would be a very strong indicator of human activity. The stump fires also have a different physical conformation from hearth “bowls.”

Bone lying on the surface during a wildfire can clearly become charred, even in rapidly passing grass fires. Paradoxically, meaty bones appear far less likely to become charred. The coincidence of charring and butchery marks on bone, as at Swartkrans (Brain 2005; Brain and Sillen 1988; Pickering 2012), appears to argue far more strongly for human fire use than does charring of bone alone. Again, points made about repeatedness of human fire use in one locality are relevant (Alperson-Afil and Goren-Inbar 2010; Gowlett 2010); repeated fires may well be necessary for bones with combined evidence of charring and butchery to result in any number.

In these experimental fires animal dung turned out to be one of the most important factors in the prolongation of burn-
ing. It can frequently be seen smouldering after a fire front has passed, and it does not seem speculative to suggest that hominins would have been aware of this. The gathering and carrying of burning dung could have been one of the first steps for hominins becoming engaged with fire use. It is worth restating another point, that natural fire is rarely a good chef. On numbers of occasions, here and elsewhere, we have noted that a fire passes too fast to complete cooking, or conversely, it may burn eggs completely. There would be a strong incentive for hominins following fires to intervene, even to a minor degree, to improve the quality of cooking either by putting food resources back into the fire or pulling them out. The signs of continued burning behind the fire front in dung and stumps might be a strong pull to humans to engage in that kind of activity.

If foraging is the most natural route into fire using, as might be suggested by the large numbers of bird and animal fire followers (Berthold, Bauer, and Westhead 2001; Gowlett 2010), it would require for hominins a very detailed knowledge of potential resources and the way in which these could be managed—the beginnings of “fire farming,” which can be seen as a somewhat different problem from the origins of hearth fire that are the focus of many studies.

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Ethnoarchaeology of Paleolithic Fire
Methodological Considerations

by Carolina Mallol and Auréade Henry

Most of the ethnoarchaeological literature on hearths is scattered within general works that target many different aspects of foraging or hunter-gatherer societies. Although these works are a good source of ideas and clues for the interpretation of macroscopically observable features of Paleolithic hearths, there is hardly any high-resolution ethnoarchaeological reference material with which to compare microstratigraphic evidence of archaeological fire. Our ethnoarchaeological research at this scale has focused on exploring differential preservation of open-air hearths and the potential to identify fire-related activities and different variables of fire technology (fuel, temperature, and function) using micromorphological and anthracological analysis. Although these studies have been useful sources of analogy, further case studies as well as ethnoarchaeological examples of superposed and imbricated hearths and reference material from enclosed settings such as caves and rock shelters are strongly called for. In this paper we summarize and discuss aspects of our previous work to highlight the strengths and weaknesses of the ethnoarchaeological approach for the study of Paleolithic fire and propose possible avenues for future research on the topic.

Fire has played a fundamental role in the biological and social evolution of humankind. Omnipresent in the domestic and ritual spheres since Paleolithic times, it has been influential for our diet and associated with the emergence of technological, sociological, and artistic expressions in different past societies (Perlès 1977). However, despite its potential to furnish valuable behavioral information on our most distant past, anthropogenic fire has been an elusive topic in prehistoric research. Most researchers have focused on trying to establish the presence or absence of fire in Paleolithic contexts in order to ascertain the timing of fire control and use, rarely examining the evidence in order to better understand human lifeways.

Nevertheless, there is a growing number of studies on archaeological combustion structures, combustion residues, and other elements of the archaeological record bearing traces of burning. Such archaeological remains convey not only socioeconomic, dietary, and paleoenvironmental information but also clues to site formation and taphonomy. All of these aspects are central to Paleolithic research. Accordingly, recent methodological approaches from different archaeological sub-disciplines (particularly geoarchaeology, archaeobotany, and zooarchaeology) have contributed valuable data to advance our knowledge of Paleolithic fire and fire-related activities (Aldeias 2017; Alperson-Afil 2017; Costamagno et al. 2009; Illubik et al. 2017; Holdaway, Davies, and Fanning 2017; Mentzer 2014; Théry-Parisot, Chabal, and Costamagno 2010).

Among these approaches, bioarchaeological analyses (in the sense of analysis of organic materials) of combustion remains—commonly charcoal, but also bone or phytoliths—provide valuable taphonomic data in relation to fuel management and hearth functionality, thus allowing us to better understand environmental and economic aspects of past societies (Théry-Parisot, Costamagno, and Henry 2009). Similarly, geoarchaeological analyses of hearths or combustion structures, which are in fact sedimentary artifacts, contribute similar kinds of information in addition to an understanding of the hearths’ formation processes (Goldberg, Miller, and Mentzer 2017; Mallol, Mentzer, and Miller, forthcoming; Mentzer 2014).

With increasing studies of anthropogenic fire in Paleolithic archaeology, it has become relevant to incorporate this topic into the ethnoarchaeological research agenda. Some archaeological sub-disciplines, such as zooarchaeology, have incorporated ethnoarchaeological research into their interpretive framework (Abe 2005; Costamagno and David 2009; Kent 1993; Monahan 1998; Sázelová et al. 2015; Svoboda et al. 2011; Waguespack 2002). Over the years, ethnoarchaeological research has also incorporated a microscopic scale of observation, as in the study of ethnographic artifacts as reference data sets for archaeological use-wear analyses (Beyries 1995; González-Urquijo, Beyries, and Ibáñez 2015; Mansur 1983). Despite these efforts, the ethnoarchaeological fire record is...
understudied, and the reason might be that fire residues are predominantly sedimentary in nature (ash and minute charred residues embedded in sediment) and the study of the sedimentary context in ethnoarchaeology is relatively recent, with only a few published case studies (see Friesem 2016 for a review on this topic).

In this paper we first briefly review and discuss the role of fire in ethnoarchaeological research applied to Paleolithic archaeology and then summarize and discuss two examples of our previous research on fire in ethnoarchaeological contexts. Our goal is to highlight the kinds of questions that can be addressed by studying the ethnoarchaeological record of anthropogenic fire and possible pitfalls. We also set forth a few methodological guidelines that, based on our experience in geoarchaeology and anthracology applied to ethnoarchaeological contexts, may aid in procuring useful ethnoarchaeological data toward an understanding of archaeological combustion structure formation processes.

Ethnoarchaeology and Paleolithic Archaeology: The Role of Fire

Why have the hearths of contemporary traditional societies not been studied in-depth to advance Paleolithic research? Ethnoarchaeological data have been an important source of information in Paleolithic archaeology, from Binford’s exhaustive documentation on the Nunamiut of northcentral Alaska (Binford 1978) to other referential studies on hunter-gatherer societies around the globe (e.g., Beyries and Pétrequin 2001; Beyries and Vaté 2007; Brooks and Yellen 1987; Fewster and Zvelebil 2001; González-Ruibal, Hernando, and Politis 2011; Kelly 1995; Leroi-Gourhan and Leroi-Gourhan 1989; Lim 1985; O’Connell 1987; Peterson 1971, 1973; Pétrequin 1988). Traditional ethnoarchaeological data concern material and spatial aspects of human behavior analyzed with a holistic approach in order to understand the link between material culture and social structure and beliefs (Binford 1980:5).

Concerning fire, Binford set forth hypotheses about hearth function, such as in his interpretation of certain archaeological combustion features as smudge pits based on ethnoarchaeological observations (Binford 1967). He also used ethnoarchaeological data to approach areas of human activity and to identify some of the factors of archaeological assemblage formation (e.g., Binford 1978). For instance, ethnoarchaeology-based models such as Binford’s “hearth-related assemblage,” “toss and drop zone” (Binford 1978), or collector/forager models (Binford 1980) have been widely used to interpret intrasite archaeological spatial distribution patterns and to infer intersite Paleolithic settlement dynamics, respectively. Actually, the study of settlement dynamics elements such as territorial mobility or site type has relied heavily on ethnoarchaeological information (e.g., Binford 1980; Brooks and Yellen 1987; Cameron and Tomka 1996; Grøn 2005; Kuznetsov 2007).

On the whole, it is generally difficult to obtain detailed information about fire-related practices based on the existing published ethnographic/ethnoarchaeological works. Besides Binford’s work, the ethnographic/ethnoarchaeological literature containing information on fire is mostly scattered within general works about the daily life of particular societies, and very few address technical issues of fuel selection and fire management. Nevertheless, cultural-ecological studies including fire as part of both symbolic and economical practices commonly provide examples of fuel type selection and management, fire functionality and techniques used in cooking fires, duration, spatial distribution, and the entity of group members in charge of fire in a number of published studies on such topics (e.g., Brandisiuskas 2007, 2010; Gur-Arieh et al. 2013; Lavrillier 2005; Osgood 1970 [1936]; Picornell Gelabert, Asouti, and Allué Martí 2011; Sillar 2000).

Other factors—such as burning temperatures, hearth re-lighting, reworking of ashes, or charcoal dispersal and micro-anatomy—are less present in ethnoarchaeological accounts (with exceptions such as Ntinou 2002; Zapata Peña et al. 2003). Such factors, which are particularly significant in the interpretation of Paleolithic fire because they can be approached through the archaeological record, often emerge from questions raised by the study of the sedimentary archaeological record or the bioarchaeological record (i.e., charcoal and other organic residues) at microstratigraphic/microscopic scales of observation, which are generally overlooked in ethnoarchaeological contexts.

As pointed out by Goldberg and Macphail (2008) and more recently by Friesem (2016), geoarchaeology and bioarchaeology did not incorporate ethnoarchaeological investigations into their agendas until very recently. The application of geoarchaeology to ethnoarchaeological contexts, or geo-ethnoarchaeology (a term coined by Brochier et al. 1992), is a relatively young field with great potential for advancing our understanding of formation processes of archaeological sites and features. So far, there are few exploratory geo-ethnoarchaeological studies, and these have focused on the micromorphological and geochemical identification of activity area sedimentary indicators (e.g., Anderson et al. 2014; Brochier et al. 1992; Shahack-Gross, Marshall, and Weiner 2003; Shahack-Gross et al. 2004; Wattez 1992), post-depositional processes affecting household elements (Friesem et al. 2011, 2014a, 2014b; Goldberg and Whitebread 1993), and the sedimentary manifestation of different kinds of open-air hearths (Mallol et al. 2007).

Within the field of fire analysis, a few studies have undertaken investigations of ethnoarchaeological contexts related to fire by focusing on different types of fuel, mainly dung and wood. Only the most recent ethnoarchaeological studies on the use of dung among traditional societies include sampling protocols that aim at producing reference data sets for identifying the use of dung as a fuel within archaeological cooking structures (Gur-Arieh et al. 2013; Lancelotti and Madella 2012; Lancelotti, Ruiz-Pérez, and García 2016).

Regarding wood fuel, even though the potential benefits of incorporating ethnoarchaeology into charcoal analysis were pointed out more than 20 years ago (Chabal 1994), “ethno-
anthropology” (Henry 2011; Henry, Théry-Parisot, and Voronkova 2009) has only been applied to very few ethnographic charcoal assemblages (Henry and Théry-Parisot 2014a; Joly et al. 2009; Nitou 2002; Vidal-Matutano 2013). The aims of such studies have been to assess the paleoecological accuracy of charcoal analysis and/or to explore the extent to which different methods are able to identify human practices.

In sum, although there have been ethnoarchaeological approaches to Paleolithic fire since the 1970s, these have rarely focused on combustion residues, which are direct transmitters of environmental and behavioral information. In recent years, with the prominence of interdisciplinary studies in archaeology, the anthropogenic combustion record in the ethnoarchaeological context is starting to be queried, and Paleolithic archaeology can largely benefit from such a source of analogy.

Research Avenues for the Ethnoarchaeological Study of Fire: Lessons from Previous Case Studies

Given an interest in hearths and hearth-assemblage formation processes, we aim at approaching some of the factors involved in the formation of archaeologically observable features formed throughout the depositional and post depositional history of a hearth. Such features may include thermally altered sediment, artifacts and bone fragments, 1–5 cm layers of ash or carbonaceous matter, and concentrations of charcoal fragments of different sizes. In practice, this is no simple task. The ethnoarchaeological context is complex and might lend itself to infinite query. Also, every case study is unique in the kinds of human actions performed around fire as well as in the nature and condition of the local sedimentary substrate. Thus, it is likely that specific questions and analytical parameters arise not only in the beginning but also during the course of the investigation once the researchers are familiarized with the site. In the case of ethnoarchaeological fieldwork for the study of hearths, familiarization with the site includes gaining basic knowledge of the sedimentary context, that is, the substrate of anthropogenic fire. We point this out because ethnographic research does not usually focus on sedimentological descriptions.

The motivation underlying ethnoarchaeological research design may be (1) to test existing behavioral or taphonomic interpretations derived from archaeological or experimental data, which will likely involve specific questions and analytical parameters, or (2) to document the material expression of particular human actions and their modification through time, which may lead to open-ended, exploratory studies. In the following paragraphs, we provide two examples to illustrate both kinds of motivation and highlight some of the results and implications for each case.

The Hadza Study on Open-Air Hearths

The Hadza study (Mallol et al. 2007) was designed as a test of the visibility of previously established micromorphological features associated with anthropogenic fire (such as browning-reddening, fissuring, and soil organic matter carbonization) in days-old to months-old open-air hearths made by a group of Hadza foragers (Tanzania) and documented ethnographically. To this end, the ethnographers collected a series of undisturbed micromorphology sediment blocks from abandoned open-air, cooking, and sleeping hearths (fig. 1). Some of the hearths were recent (days old), while others had been abandoned for 1 year. Regarding the duration of these fires, some of them were continuously used for 3–4 months, while others were brief fires (less than an hour in duration) for roasting food items.

The results of this study, detailed in Mallol et al. (2007), included field and micromorphological observations on the sedimentary substrate associated with the abandoned hearths. At a microscopic scale, all the samples, including those from hearths that had been abandoned for a year, yielded combustion residues (wood ash, charcoal, and charred plant/animal tissue) attesting to the presence of anthropogenic fire as well as microstructural sedimentary features such as matrix disaggregation and browning or “masked birefringence.” Overall, the micromorphological components and features observed are in agreement with those proposed by Wattez (1992) as representative of moderate to high intensity hearths involving temperatures from 350°C to >500°C.

Certain micromorphological differences relating to function were observed among the different types of hearth. For instance, the sedimentary substrate of a brief fire made to roast an impala yielded a few amorphous black impregnations and coatings (fig. 2A), and a tuber-roasting fire left behind microscopic charred plant tissue fragments (fig. 2B). Before this study, it was unknown whether or not specific activities related to anthropogenic fire might leave microscopic material evidence in the sediment. Unfortunately, these particular hearths were sampled only days after they were made, and we do not know the preservation potential of the observed features. There were also micromorphological differences relating to taphonomic factors. The hearths sampled 1 year later showed presence of ash only in a case where a layer of dry grass from a dismantled hut had covered the hearth. They also showed signs of bioturbation (channels and fresh rootlets dissecting the top of the combustion structure; see fig. 2C), whereas those that were days or months old did not (fig. 2D). Interestingly, bioturbation did not affect the sedimentary fabric to the extent of precluding identification of combustion features.

The study also showed that micromorphology is a powerful tool to approach the genesis of sedimentary deposits through a very peculiar finding: one of the samples showed micromorphological features indicative of the presence of an abandoned hut floor beneath one of the open-air hearths. The previous existence of a hut at the spot of that particular hearth had not been reported ethnographically. This finding shows that geoethnoarchaeology performed at a microstratigraphic scale of observation adds a temporal dimension, thus contributing historical information. This contribution may help alleviate a shortcoming of ethnoarchaeology pointed out by Wobst (1978): “The ethnographic record is insufficiently sensitive to deal with be-
The living social context is complex and we can only attempt to perceive a limited range of its material expressions. By incorporating historical information, we broaden the scope of possibly interrelated material expressions. Overall, our results provided an example of what different kinds of simple anthropogenic fires might leave behind in ethnographic contexts after up to a year’s time. In this regard, the results suggest that rates of sedimentation and the effect of postdepositional disturbance factors such as bioturbation or erosion are key factors in the preservation of open-air simple hearths. Erosion by rain and deflation seemed to be particularly influential, as we saw that the ash layer of a hearth that had been protected by a light grassy cover was still intact after a year in the open-air while those of exposed hearths had disappeared, or that the ash of a 10-day-old hearth dissipated after a single rainfall event. The Hadza example also showed that even though the ash component is likely to erode away with time in cases of low sedimentary rates and deflation, the irreversible effects of fire in the top 2 cm of the sedimentary substrate (charring of soil organic matter and clay alteration) may remain intact and be readily identified through micromorphology.

Figure 1. Different types of Hadza hearths subjected to micromorphological analysis. A, Brief, 20-minute-long fire used to burn an impala and sampled 10 days later. B, Cooking hearth used recurrently for 4 months and sampled a year later. C, Abandoned sleeping hearth at the entrance of an abandoned hut. It was lit every night for 4 months, and the sample was collected a year after abandonment. Note the layer of dry grass over it. D, Communal cooking hearth used continuously for 3 months and sampled 2 months later. E, Brief (15 minutes) tuber-roasting fire that was sampled the day after. A color version of this figure is available online.
lined or stone-hearths, which are generally more complex, involving stone-associated with Upper Paleolithic and Mesolithic open-air combustion features. A color version of this figure is available online.

All these observations can be useful in the interpretation of Paleolithic fire evidence. Unfortunately, micromorphologica studies of Paleolithic open-air combustion features are scarce. The bulk of data was gathered by Wattez in the 1990s and is associated with Upper Paleolithic and Mesolithic open-air hearths, which are generally more complex, involving stone-lined or stone-filled pit structures (e.g., Wattez 1992, 1994). Therefore, there is not much data allowing us to make analogies with the results of our study of simple Hadza hearths. One case is the Middle Paleolithic open-air site of Nesher Ramla, Israel, where an in situ simple combustion structure and a wood ash midden were reported by Friesem, Zaidner, and Shahack-Gross (2013). The sediments from the combustion structure showed a thin black layer composed of blackened sediment aggregates overlain by wood ash residues and calcined bone fragments (Friesem, Zaidner, and Shahack-Gross 2013).

According to the authors, preservation of these features was possibly enhanced by their location in a topographic depression sheltered from the wind and receiving regular colluvial input, which would have buried the intact features. This interpretation is in agreement with our observations from the Hadza hearths, as we would not expect long-term preservation of ash in such simple open-air combustion features otherwise. The amount of ash reported for the in situ hearth at Nesher Ramla is quite small, suggesting either some period of deflation or erosion from rain before burial. Regarding the charred substrate, the presence of blackened soil aggregates suggests a more organic-rich substrate than what we documented in the Hadza study, which was practically barren land with a light grass cover.

In sum, the Hadza study showed the value of performing high-resolution, microstratigraphic investigations of the ethnoarchaeological sedimentary record to distinguish between natural and anthropogenic fire, to estimate burning intensities, to identify fuel types, and to assess preservation potentials. In hindsight, the study would have yielded more detailed results if we had included the following items in the research design: (1) the presence of a geoarchaeologist on site to enrich the ethnographic record with data relevant for the study of site formation, and (2) the implementation of techniques complementary to soil micromorphology. Current geoarchaeological combustion structure investigations are normally carried out from a microcontextual perspective using interdisciplinary microstratigraphic methods (see examples in Mentzer 2014) and involving techniques from inorganic and organic geochemistry and geophysics, including, for example, organic petrology for identification of microscopic charred particles, Fourier Transform Infrared Spectrometry for mineral identification, gas chromatography mass spectrometry for lipid analysis, or archaeomagnetism to approach firing temperatures and temporal relationships between different hearths. Applying such techniques in the Hadza study might have strengthened the reliability of such techniques to provide data on thermal alteration of the substrate and to identify combustion residues.

Finally, in order to further expand the results obtained in the Hadza study toward an understanding of Paleolithic combustion structures, the results need to be tested against experimental taphonomic data on abandoned open-air hearths and also against micromorphological data from ethnoarchaeological examples of hearths in enclosed settings (caves or rock shelters) as well as examples of superimposed and imbricated hearths, which are common in the Paleolithic fire record. No such data are currently available.

The Evenk Study of Specialized Open-Air Hearths

The Evenk research program was first designed as a case study to test a model proposed for the European Paleolithic according to which fuel management is a complex system resulting from a series of interacting environmental and cultural parameters (Théry-Parisot 2001). An exploratory study was carried out among a group of Evenk reindeer herders and hunters from the Amur Region (South Eastern Siberia) in order to (1) observe firewood management practices from wood acquisition to the discard of fuel residues; (2) observe possible connections between the environment (available...
burning on a bed of relatively fresh plant litter (3 cm fragments of rotten wood without any visible signs of the combustion deposit consisted of a mix of charcoal and 1 required dismantling of the hearth.

Fieldwork among the Evenks was carried out in two seasons, one in late winter/early spring, and another in late summer/early autumn. Throughout the study, we observed that Evenk traditions are strongly influenced by seasonality and residential mobility. These factors have a decisive effect on the range and configuration of activities performed at their camps (which in archaeological terms would determine the site’s function). This observation also applies to combustion structure types, their function, and firewood management, with wood procurement areas and modalities varying according to the time of year (Henry 2017; Henry, Théry-Parisot, and Voronkova 2009). In turn, combustion structure types and functions determined the species and state of the selected wood. In Paleolithic research, seasonal constraints have mainly been approached through subsistence studies. By showing that a whole range of activity areas—firewood management included—are strongly tied to seasonal and climatic conditions, this example invites us to expand our approach of seasonality, prehistoric settlement patterns, and mobility.

Furthermore, the study confirmed the positive correlation between the degree of fuel selectivity and of hearth specialization implicitly suggested in earlier anthracology works (Chabal 1982, 1991) as well as the importance not only of the taxon but also of the state of the wood in the wood selection process (Théry-Parisot 2001). In turn, the implications for prehistoric anthracology are that the identification not only of the taxon but also of the state of the wood used is crucial for the characterization of prehistoric wood procurement modalities, combustion behavior, and the specialized/seasonal nature of the hearths (see also Henry and Théry-Parisot 2014b; Théry-Parisot and Texier 2006).

Finally, the relationship between two kinds of fireplaces and anthracological/micromorphological signatures were explored during the second field season, in which our Evenk hosts were kind enough to allow us to collect charcoal from a smudge fire and to excavate and sample their hide-smoking hearth for charcoal and micromorphological analyses (fig. 3). We excavated half of it, collecting anthracological samples, and saved the other half for micromorphological sampling, which required dismantling of the hearth.

 Micromorphological observation of three thin sections from the hide-smoking hearth, which produced no ash, showed that the combustion deposit consisted of a mix of charcoal and 1–3 cm fragments of rotten wood without any visible signs of burning on a bed of relatively fresh plant litter (fig. 4). A few rotten wood fragments were also observed embedded in the plant litter layer (fig. 4A). Rotten wood has a low preservation potential under aerobic conditions. Thus, encountering such evidence in archaeological context is infrequent, and we can assume that identifying the presence of residual rotten wood in an archaeological version of this hearth would require investigations at a molecular scale. The same can be said about the substrate, which consisted exclusively of fresh plant litter without any apparent effects from the overlying combustion. This is explained by the way in which the fire was made: a small quantity of charcoal from sound wood was produced in a furnace elsewhere and redeposited on the ground at the hide-smoking spot, where it was then covered by rotten, crumbling wood.

Interestingly, our microscopic observations suggest that similar hide-smoking hearths might have been previously made at the same place, as indicated by the presence of rotten wood—an intrusive element brought by humans—contained within the plant litter substrate. As in the Hadza case, micromorphological analysis yielded information on past events. As we know from the Evenks we worked with, they normally return to their main campsites yearly, at least for periods of 4–5 years, and light their fires at the same spots as in previous occupations.

In sum, we can predict that a possible archaeological expression of a hide-smoking combustion structure of the kind studied here, after many years of subaerial exposure, would exhibit a very weak sedimentary signature consisting of a diffuse layer of charcoal resting on an unburned sedimentary substrate.

Regarding our anthracological results, both hearths (smudge fire and hide-smoking hearth) were positively discriminated and allowed us to set forth a new method to diagnose the initial soundness of firewood based on the identification of micromorphological fungal alteration intensities observed on charcoal fragments (Henry and Théry-Parisot 2014a; fig. 5). This method has proven to be effective for discussing fuel management strategies evidenced in Paleolithic and Mesolithic hunter-gatherer sites (Henry and Boboeuf 2016; Henry and Teten’kin 2014; Vidal-Matutano, Henry, and Théry-Parisot 2017).

These results have several implications for Paleolithic anthracology because they evidence the nature of the link between environmental conditions, lifeways, and modalities of fire use. As in other research domains, comparisons with other ethnographic settings point at the great variability of practices and beliefs around fire. Nevertheless, regularities also exist between different groups, revealing similar choices under comparable environments (Henry 2011). For example, the use of crumbling rotten wood for smoking hides is ubiquitous among northern hunter-gatherers living in forest environments from Siberia to North America (Alix and Brewster 2004; Anikovskij et al. 2012; Beyries 2002, 2008; Binford 1967; Brandisauskas 2007, 2010; Henry, Théry-Parisot, and Voronkova 2009; Lavrillier 2007; Nelson 1986; Osgood 1970 [1936]). The prospect of being able to discuss archaeological hearth functions thanks to new developments in ethnoanthracology is particularly exciting and motivates new archaeoanthracological studies geared in this direction. One such study involves a hypothetical Middle Paleolithic smoking hearth based on archaeoanthracological data (Vidal-Matutano 2016; Vidal-Matutano, Henry, and Théry-Parisot 2017).

biomass), human activities, and fuel management; (3) assess which of these observations could be evidenced by the study of anthracological remains and sedimentary micromorphological signatures; and (4) explore the possibility of tracing analogies between current nomadic lifeways in cold environments and Paleolithic contexts (Henry 2011; Henry and Théry-Parisot 2014a; Henry, Théry-Parisot, and Voronkova 2009).

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Figure 3. Summary of the ethnoanthracological work with Evenki from Ulgen, Amur Region. Photos: Aurèade Henry, ACI "Système Renne." A color version of this figure is available online.
The downside of the Evenk study is that the limited amount of hearth samples is insufficient to fully evaluate the potential and limitations of our results. Also, as with the Hadza study, applying complementary geoarchaeological techniques would have allowed for richer, more robust data. In the future, many more hearths need to be sampled in order to obtain a stronger reference data set and establish a protocol that incorporates multiproxy geoarchaeological and bioarchaeological data.

A final observation is that studying hearths that are still in use has many advantages, because complete operational chains (chaînes opératoires) of specific activities such as meat curing or hide smoking can be documented as well as their timing and duration, fuel amounts and procurement distances, and other such variables involved in fire technology. However, one disadvantage is that sampling can be difficult or even impossible because it involves destruction of a structure within or outside the perimeter of ongoing domestic activity. Some of these structures may have a strong cultural or symbolic meaning for the community.

Methodological Guidelines

The two examples presented here convey a series of aspects to take into consideration when designing an ethnoarchaeological project to study contemporary simple hearths comparable to Paleolithic counterparts. Among the things to consider are planning for the implementation of interdisciplinary methods to test the preservation state of the target features before intervention. In this section, we provide a few more specific and practical guidelines that may facilitate the research design.

1. Compile ethnographic data and assess their quality. What is the potential of this data to answer archaeologically relevant questions regarding anthropogenic fire? When a pertinent research context has been defined, it is equally important to assess the marginality of the recorded activity or process: is this type of behavior recurrent today among traditional societies and at what scale? What other related social and environmental domains need to be described?

2. In the case of abandoned contexts, which may be exposed or buried, assess the degree of integrity of the record through surveys and test pits. For each proxy, control samples from nearby natural deposits or activity areas should also be collected to validate the diagnostic value of the results.

3. Perform excavation and collect sediment samples for multiple microstratigraphic analytical techniques. Unlike other ethnoarchaeological remains, such as exposed remains, combustion structures representing open hearths can be difficult or even impossible to study. Therefore, it is crucial to establish a protocol that incorporates multiproxy geoarchaeological and bioarchaeological data.
always require excavation because of their sedimentary nature. Excavation and sampling may be performed following a protocol for archaeological combustion features. We propose to follow these steps (fig. 6):

a. Determine the perimeter and plot it within a coordinate system.

b. Divide the feature in two equal portions and excavate half of it, leaving the other half for microstratigraphic sampling. Excavate following stratigraphic layers and place the sediment from different layers in different bags. If possible, collect all the sediment for future studies on fuel loss, ash yield, etc. This sediment will be subsequently sorted to recover different kinds of macroremains (charcoal, seeds, bone fragments, microfauna, etc.). In cases of occurrence of anthropogenic bone remains other than fuel or artifacts, these should be plotted as material remains within the coordinate system, including their depth.

c. While collecting samples from the second half, keep all the remaining sediment and piece-plot any artifact, bone, or other visible anthropogenic object. Keep in mind that different analytical techniques (e.g., soil micromorphology, organic and inorganic geochemistry, archaeomagnetism, analysis of phytoliths, spherulites, and pollen if applicable) require different specific sampling protocols.

d. Collect control sediment samples (or hand specimens in the case of macrobotanical studies) from outside the combustion structure for each of the analytical techniques.

Discussion: Some Pros and Cons of Ethnoarchaeological Research to Approach Paleolithic Fire

Ethnoarchaeology may be viewed as a polemic field of research because at first it seems rather impossible, if not dangerous and unscientific, to use ethnographic data for the interpretation of archaeological evidence. Societies are complex dynamic systems fashioned by multiple interrelated factors across space and time. Some authors are pessimistic about the potential of ethnoarchaeology unless it is carried out through an ontological approach (González-Ruibal, Hernando, and Politis 2011).
In practice, this means that in the study of a particular aspect of human behavior, such as behavior around fire, researchers need to adopt a broad perspective and include other behavioral domains in order to approach more general aspects of societal and/or environmental value. In other words, anthropogenic fire, as any other element of human social behavior, must be considered within its social and environmental context. Thus, ideally, the ethnoarchaeological research team involved in a study of fire behavior should include experts from different fields documenting as many aspects of culture and environment as possible.

Another polemic issue is the validity of ethnographic analogy. Present-day observations should not be directly transposed to the past. Caution should be taken when using contemporary societies to approach distant spatio-temporal contexts (e.g., comparing present-day subtropical agricultural societies with Paleolithic hunter-gatherers of the Northern Hemisphere) or tracing analogies that may seem straightforward (e.g., Bronze Age vs. present-day traditional pastoral societies of the same area). In all cases, it is important to bear in mind that “the true role of ethnoarchaeology is not to provide the prehistorian with analogical tidbits, but rather to be an important source for those wanting to build theoretical models for the relationships between people and things” (Skibo 2009:47). As shown by our own work, ethnoarchaeology also provides insight into site formation processes and the nature of our archaeological remains (including sedimentary residues).

The challenge lies in achieving ethnoarchaeological research design in a way that meets the standards of current archaeological science. There are very few general works on ethnoarchaeology (e.g., David and Kramer 2001) that include methodological guidelines geared at multidisciplinary research and the incorporation of subdisciplines such as bioarchaeology and geoarchaeology. Despite this, the existing literature reveals that ethnoarchaeology may truly benefit most fields of prehistoric research as long as two main targets are pursued: (1) obtaining contextualized ethnographic data through interdisciplinary approaches and (2) carrying out research motivated either by archaeological facts and questions or by a need to obtain reference material for the material residues of specific human activities or lifestyles.

According to our personal experience in the field of the ethnoarchaeology of fire, it has become obvious that ethnoarchaeology is much more than a “real-size experiment.” Ethnoarchaeology not only improves our reference data sets (and in this sense, it is complementary to experimentation) but also provides an enriching way of approaching the archaeological record through the possibility of apprehending the diversity of environmental and societal variables and their effect on the material record.
The Hadza and Evenk studies are good examples of how ethnoarchaeological research may generate new knowledge that is complementary to archaeology and experimentation. In the Evenk case, while showing that the archaeological model was easily adaptable to any fuel management study, our observations also revealed complex patterns of human behavior toward firewood, which could only be understood in regard to the social, economical, and seasonal background of the study. In return, these results provided us with new ideas for interpretative pathways of prehistoric fuel selection and hearth function in relation to site function and seasonality.

The challenge was then to test the potential of archaeological methods to document socioeconomic aspects through the study of their material expression: combustion structures. The positive results of the ethnoanthrological analysis, which have been subsequently validated by substantial experimental replication (Henry and Théry-Parisot 2014a), opened up new methodological perspectives on fuel selection, hearth function, and even seasonality.

In sum, ethnoarchaeology is complementary to but not replaceable by experimentation, because functional and meaningful anthropogenic deposits or sedimentary features are difficult if not impossible to produce outside their traditional context. On the other hand, experimentation can and should be used to further investigate and validate ethnoarchaeological results before testing their applicability to archaeological contexts. At a broader, systemic scale, ethnoarchaeology of fire is a powerful tool to evaluate the variability of human adaptations to the natural environment through the establishment of causal relationships between culture and fire technology.

Conclusions
This holistic, multidisciplinary approach, which allows us to take into account many different environmental and material and nonmaterial parameters influencing the nature of the anthropogenic combustion remains, aims at contributing to the development of new analytical methods for the study of prehistoric combustion structure formation processes, fuel management systems, and hearth function. We have shown that ethnoarchaeological research, whether motivated by the need to test experimental or archaeological interpretations or by exploration, requires case-specific questions and analytical parameters. Our two case studies are examples of the great potential in applying geoarchaeological and bioarchaeological techniques and have allowed us to identify several important factors that should be taken into account in future research design. These include the presence of specialists on site and application of multitechnique microstratigraphic studies.

So far, our work has provided pilot micromorphological and anthracological data that contribute to the study of Paleolithic fire. However, it needs to be expanded significantly in different ways. We now have a few examples of open-air hearths that need to be complemented with examples of hearths from enclosed settings such as caves and rock shelters and enriched by geoarchaeological and bioarchaeological data from additional techniques. It is to be hoped that further research of this kind will be carried out in the coming years and that it will contribute data to aid in building robust reference data sets for our understanding of Paleolithic hearth and hearth-assemblage contexts through ethnographic analogy.

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Mallol and Henry Ethnoarchaeology of Paleolithic Fire

S229

Aboriginal Use of Fire in a Landscape Context
Investigating Presence and Absence of Heat-Retainer Hearths in Western New South Wales, Australia
by Simon J. Holdaway, Benjamin Davies, and Patricia C. Fanning

A case study from western New South Wales, Australia, illustrates the age, preservation, and distribution of late Holocene heat-retainer hearths that are abundant in the semiarid archaeological record in the region. These hearths were constructed as underground ovens with stone heat retainers. They appear archaeologically as eroded concentrations of heat-fractured stone sometimes protecting charcoal deposits. We explore geomorphic processes influencing hearth temporal and spatial distributions using a neutral agent-based model. Parallels between model outcomes and the distribution of hearths in space and time suggest that processes of sediment erosion and deposition are having complex effects on hearth survivorship and therefore on patterns of hearth frequency. We consider the various processes that explain why hearths were made in the past and how they manifest in the present. Despite the relatively recent age of the hearths when compared with evidence for fire use in the Paleolithic record, the presence and absence of these fire features reflect the outcome of a large number of processes interacting together, not all of them related to human behavior. We use the results of the case study to comment on current behavioral models for the presence and absence of fire use in the distant past.

Human use of fire in the semiarid regions of Australia is visible archaeologically as abundant heat-retainer hearths that are found in eroded contexts along drainage lines. These hearths appear as concentrations of heat-fractured rocks clustered together with tens to thousands of heat-retainer fragments. In some hearths, these heat retainers protect charcoal deposits. However, as we discuss below, many of the hearths are eroding, and once exposed, the charcoal is also susceptible to erosion. The distribution of these hearths is of particular interest because they do not conform to a pattern consistent with occupation sites and they are not the remains of broadcast firing used to concentrate game or modify flora. Instead, these hearths were constructed in almost all parts of drainage lines.

Such a distribution is not unique to semiarid Australia, being reported in some other parts of the world where surface exposure is favorable (e.g., Black and Thoms 2014; Brink and Dawe 2003; Milburn, Doan, and Huckabee 2009; Petraglia 2002; Schaefer et al. 2014; Sullivan et al. 2001; Thoms 2009). In common with the Australian example, the distribution of these fire features indicates an additional aspect of “on site” and “off site” fire use. Yet despite their ubiquity in different areas of the world, fire use in these settings has received relatively little attention. Here we outline the archaeological expression of this form of fire use in one part of semiarid Australia. In doing so, we emphasize how fire use can be understood as a set of inter-connected relationships between people and environment in the way that human use of fire manifests, in the technology of fire use, and in the ways the outcomes of fire use are preserved in the archaeological record.

An older literature commented on changes in past Australian environments as a consequence of Aboriginal fire use (e.g., Flannery 1994; Kershaw et al. 2002; Singh, Kershaw, and Clark 1981). More recently, changes in the frequency of radiometric dates from archaeological fire features have been used as primary evidence for directional changes in past human population and occupation intensity (Johnson and Brook 2011; Smith et al. 2008; Williams et al. 2015). However, patterns in large-scale records of fire are not always principally determined by human activities even when human action may have contributed to their initial creation. For example, Mooney and colleagues (2011, 2012) have shown that when large numbers of charcoal records are

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compared from across the continent, climate-modulated changes in vegetation explain more of the variation in fire prevalence than do human activities over timescales measured in centuries to millennia, a finding that parallels the results of global studies (Bowman et al. 2009, 2011). If patterning in archaeological fire features is to be used to understand past human behavior, then behavioral contributions to those patterns need to be contextualized within the larger suite of formational processes operating on landscapes over time.

The reasons that hearths constructed in different places are found, the form that these hearths took, and the archaeological preservation of these hearths can be understood by considering fire use in relation to environmental and geomorphological history before behavioral inferences are drawn. While the history of fire use in semiarid Australia is of interest in itself, the case study reported here also has wider relevance for studying human use of fire. The types of archaeological signatures fire use produces will vary contextually, and inference about fire use needs to be assessed accordingly. The Australian case study illustrates that where consideration of the influence of these contexts on the formation of patterning associated with fire use is absent, behavioral inferences drawn from the presence or absence of fire features in the archaeological record may be misleading. This particularly applies to studies that rely on the absence of evidence for fire use (e.g., Roebroeks and Villa 2011; Sandgathe et al. 2011).

How fire manifests archaeologically is partly determined by the contexts in which people found fire useful, and these contexts in turn shape the archaeological record that preserves it. Fire functions are not self-evident in the sense that fire needs to be treated in relation to the ways people and objects interacted with past environments before its presence or absence can be understood. This relates to the way fire is employed by humans but also to how the material remains are preserved, itself the outcome of the interaction of the material remains of fire and a variety of environmental and geomorphological processes. Documenting such interactions from archaeological remains raises significant issues because at one level, we can only analyze what is preserved and what we can see. As is illustrated in the case study below, this issue is not confined to very ancient archaeological records.

Case Study: Hearths in Western New South Wales, Australia

The Semiarid Environment

The Rutherfords Creek study area is located on the valley floor margins of an ephemeral stream draining a catchment of 37.8 km² in western New South Wales (NSW) on the southeastern margin of the central Australian arid zone (fig. 1). The climate today is semiarid, with mean annual rainfall less than 250 mm and pan evaporation exceeding 2,000 mm (Holdaway, Fanning, and Witter 2000). As a consequence, vegetation is sparse, with chenopod shrublands ubiquitous across the hillsides and trees confined to the larger watercourses. Both of these vegetation communities provided firewood. Extensive areas of stony (“gibber”) and bare surfaces mantle the slopes and plains. Changes in vegetation cover and geomorphic processes occurred with the introduction of European-style pastoralism in the nineteenth century (Fanning 1994, 1999). Topsoil from hillsides was deposited on valley floors as laminated sandy sediments. Streams incised into the valley fills, and renewed erosion on the valley floors followed, leaving hard-setting, saline subsoils exposed at the surface on which archaeological materials, mostly stone artifacts but also heat-fractured stones from heat-retainer hearths, now rest (Fanning 1999).

Episodic flood events, resulting in erosion in some areas and deposition in others, are a feature of the study area (Fanning, Holdaway, and Rhodes 2007). Mean annual rainfall is low, but variability is high, and the bulk of the rain falls during short, intense rain depressions, especially in summer. Episodic events such as this affect the sedimentary record. Where the contemporary creek lines are cut into alluvial sequences, unconformities represent either substantial hiatuses in valley floor aggradation or, more likely, periods dominated by valley floor erosion. For example, at Stud Creek (fig. 1), gaps of several
thousand years occur in the depositional record of Holocene and late Pleistocene deposits (Fanning and Holdaway 2001). The absence of buried paleosols in these deposits suggests the unconformities represent more than just stable periods in the evolution of the landscape when aggradation temporarily ceased. Instead, it is likely that an older record of occupation was destroyed by erosion represented by the unconformities in the stratigraphic sequence (Fanning and Holdaway 2001:99).

Surface visibility, and therefore the quantity of the surface archaeological record, is highest where there is an absence of vegetation and the surface is lagged, forming “scalds” where topsoils (more correctly, the uppermost sedimentary unit) are removed by a combination of wind and water erosion (Fanning and Holdaway 2004). Stone artifacts and hearth stones are exposed on scalds as the finer sediments are removed by unconcentrated overland water flow. On slopes greater than two degrees, this overland flow can also move small artifacts with a maximum clast dimension less than 20 mm. However, lateral movement is much less discernible among the larger stone artifacts and stone heat retainers (Fanning et al. 2009). In a sense, therefore, sediment erosion has “excavated” the archaeological record, offering an opportunity for investigation of large quantities of this record distributed across the landscape.

Archaeological Survey

From 2005 to 2008, archaeological and geomorphological surveys were conducted along a 13 km length of the main channel of Rutherfords Creek on the eroding valley floor margin. Artifact deposits are visible on eroded patches (the “scalds” discussed above) making up approximately 2 km² of the valley floor. The detailed archaeological surveys were confined to a randomly selected sample of the approximately 2,267 mapped scalds, amounting to approximately 4.5% of the eroded valley floor by area.

Hearthstones were constructed by Aboriginal people in the past by excavating a depression that formed the body of an oven into which stones and then food items could be placed for cooking (Holdaway et al. 2002). Europeans who observed Aboriginal people in the nineteenth and early twentieth centuries described the construction and use of these hearths (e.g., Eyre 1845 and Parker 1905, cited in Allen 1972:280–281). In one example, Daniel George Brock, who accompanied the explorer Charles Sturt (Peake-Jones 1988), recounts how hearths were constructed by scooping out a hollow, adding oven stones, then lighting a fire to heat them and burying plant and animal food in the scoop. The oven stones aided cooking by acting as heat retainers, helping to prolong the heat generated by the fire. Recent findings from the Mungo region show that the use of heat-retainer technology is present in Pleistocene deposits in Australia (Fitzsimmons et al. 2015).

As discussed below, heat-retainer technology dated to different periods is found elsewhere in the world and, in some places, is still in use today (Petraglia 2002). In western NSW, subsequent abandonment of the hearth led to depression in-filling, burying, and preserving hearth remains. Once buried, hearths were probably difficult to identify even by the people who made them. Their presence on the surface today is a consequence of erosion processes that are both exposing them and at the same time causing their destruction and, for some, re-burial (Fanning et al. 2009).

Heat-retainer hearths were identified during archaeological surveys of Rutherfords Creek as concentrations of heat-fractured stone sometimes protecting an underlying deposit of charcoal, with 979 recorded in eroding valley floor deposits in the Rutherfords Creek study area. Heat-fractured stone can be identified by the presence of small nonconchoidal flakes shed during heating (pot lids) and by cracking patterns as well as by irregular fracture. Identification was easiest when the heat-fractured stones were concentrated together but became progressively more difficult as erosion dispersed the fragments. Identification was also dependent on the nature of the land surface on which they rest. They were, for instance, much harder to identify on surfaces covered with a gravel lag. To some degree these problems were overcome by using a fluxgate gradiometer to measure both magnetic susceptibility and thermoremanent magnetism as a result of heating (Fanning, Holdaway, and Phillipps 2009; see also Gose 2000).

Because they are exposed by erosion, the condition of hearths differs depending on the extent of this erosion. Six categories are used to describe the degree of hearth preservation (fig. 2): buried, partially exposed, intact, disturbed, scattered, and remnant. “Buried hearths” describes those that remain largely buried with only the tips of the fire-cracked rock poking above the surface (fig. 2A). “Partially exposed hearths” describes hearths where a portion of the cluster of hearth stones is exposed along an erosion escarpment (fig. 2B) but the bulk of the hearth remains buried. “Intact hearths” are those where erosion has completely exposed the dense cluster of fire-cracked rock, but it has not been dispersed (fig. 2C). The next three categories—“disturbed,” “scattered,” and “remnant”—refer to hearths displaying increasing amounts of disturbance of the heat retainers (fig. 2D–2F).

All 2,267 scalds and gravel patches identified in Rutherfords Creek were searched to determine the presence of heat-retainer hearths. In addition, the areas between the sampling units were systematically surveyed. Hearths found on the scalds and gravel patches totaled 737 with an additional 242 hearths located between the sampling units (fig. 3). The overall distribution of hearths recorded per scald or gravel patch is clustered (Moran’s $I = 0.131, z = 9.954, P < .001$). However, an Anselin Moran’s $I$ analysis indicates only two areas with substantial hearth clusters. The first is in the northeastern corner of the catchment, an area with concentrated sheet wash erosion, and a second area in the center of the catchment, where hearths are clustered in scalds that are particularly eroded. In addition, there are isolated examples where there are an unusually high number of hearths. Overall, while there are hearths visible in all parts of the catchment valley floor margins, these are not clustered in any one part of the valley.
Figure 2. Hearth preservation categories: A = buried, B = partially exposed, C = intact, D = disturbed, E = scattered, F = remnant. Source: Fanning, Holdaway, and Phillipps (2009), fig. 3.
It is worth emphasizing that the total number of hearths identified reflects only those that were visible at the times when the survey was conducted. This total therefore reflects the outcome of processes of erosion and aggradation that initially exposed hearths and in some cases destroyed them while at other times reburied them. Thus, the total number of observed hearths is a sample of a much larger number of hearths that still exist or that once existed. The patterns that we see, both in the distribution of hearths and in their ages, need to be interpreted with these processes in mind. An agent-based simulation study of hearth exposure (Davies, Holdaway, and Fanning 2015) was developed and applied to illustrate these processes, as summarized below.

**Hearth Dating**

Two hundred and fifty-six hearths of the 979 identified were excavated to obtain dating samples, including hearthstones for optically stimulated luminescence (OSL) dating (Rhodes, Fanning, and Holdaway 2010; Rhodes et al. 2009). Only about one third of the hearths excavated contained enough charcoal for radiocarbon dating. Hearths were excavated in clusters to determine whether groups of hearths shared similar or different ages. Hearths were excavated in clusters to determine whether groups of hearths shared similar or different ages.

Hearth ages range from modern to ages in excess of 6000 cal BP, with the spatial patterning depending on their geomorphic setting (Holdaway, Fanning, and Rhodes 2008). To use Cluster 11 as an example (fig. 3), the youngest hearths in this cluster are found closest to the creek channel and to the north on the true left bank. OSL sediment ages suggest that in these regions, ancient sediments are deeply buried. At OSL sample locations L and M and N and O, Pleistocene-aged sediments occur but only at depths greater than 70 cm. Near-surface sediments are more recent than 2000 BP. In contrast, sediments at location K date to around 4000 BP at 35 cm depth. Here, hearths have ages that range from 2000 to 4000 BP together with some that are more recent. Thus, the distribution of hearth ages is likely to reflect surface preservation (Holdaway, Fanning, and Rhodes 2008). The northern hearths in Cluster 11 rest on sediments that are recent in age, probably because at times in the past the creek has avulsed and removed older hearths through erosion. Ancient sediments at this location are relatively deeply buried by more recent deposits. To the south of the creek, erosion is less prevalent, leaving relatively ancient hearths intact (as determined by OSL measurements on hearthstones).

Hearth ages therefore partly reflect the age of the sediment surfaces on which they rest. However, we also know that the
hearth preservation.

Agent-Based Model of Hearth Visibility

As discussed above, patterning in the archaeological evidence for fire is often explained in behavioral terms based on inferences about hearth function derived from the contents of hearths and at times from ethnographic analogy and with limited consideration of the roles of visibility or formational processes. Frequencies of radiocarbon data obtained from hearths or other features are used to demonstrate diachronic changes in population or occupation intensity in a given location (e.g., Gamble et al. 2004; Johnson and Brook 2011; Mulrooney 2013; Rick 1987; Smith et al. 2008; Williams 2013; cf. Attenbrow and Hiscock 2015; Delgado, Acetuno, and Barrientos 2015). However, the strength of any explanation invoking behavioral change should be based on the ability to demonstrate a difference from instances when human behavior is not assumed (Brantingham 2003:490). It is therefore important to establish how different the pattern is when behavioral change is removed from the equation. Neutral models in which the formation of a given proxy is uniform are frequently used as mechanisms for developing expectations (e.g., Contreras and Meadows 2014; Rhode et al. 2014). If changes in human behavior were the primary driver in the generation of fire-related patterning in the archaeological record, then it is expected that such patterning would show little similarity to that produced by a model that assumed no variation in behavior (Brantingham 2003; Premo 2007). Similarities between the record and outcomes from a model with neutral assumptions can be used to evaluate the extent to which behavior needs to be considered as part of an explanatory framework or whether the resolution of the patterning is sufficient to distinguish it from a neutral record (Lake 2015:14).

To explore the effects of differential erosion and deposition on a uniform record of hearth manufacture that could be compared with the results obtained from the survey along Rutherford’s Creek, an agent-based model was constructed using the NetLogo modeling platform (Davies, Holdaway, and Fanning 2015). The model consists of a grid world where each cell contains an ordered list of dated sedimentary layers. In the model, computational agents construct dated hearths at a constant rate over random points on the grid during the period from 2000 to 200 BP. Any hearth with an age younger than or equal to the age of the most recent layer of sediment of the cell on which it rests is considered visible, while any that are older are hidden as part of a subsurface deposit. At given time intervals, events occur that have the capacity to erode or deposit sediment in a grid cell. If erosion occurs, the uppermost layer of sediment is removed, and any hearths visible on the surface lose their datable charcoal. If deposition occurs, a layer of sediment is added to the cell, and any hearths currently visible on the surface are hidden. Hearths that are hidden can become reexposed through subsequent erosion events. In the model, two variables are initially explored: the probability of individual cells experiencing erosion versus deposition during a given event (modeled as Bernoulli process; Jaynes 2003:42) and the time interval between these events.

Results generated from 1,000 random samples of 100 hearth ages ordered from youngest to oldest are plotted in figure 4A with separate graphs for time intervals between events of 10 to 200 years and the probabilistic difference between erosion and deposition of sediment varied between 0.1 and 0.9 (to ensure some hearths are always present). If no deposition or erosion occurred, hearths would fall along a diagonal line from 200 years BP at bottom left to 2000 years BP at top right, depending on their age. When sampled ages of surface hearths from all simulations are compared, curves all fall to the left of this line and so are weighted toward the present. Increasing the frequency of events produces a record that is younger on average, while more mixed regimes feature a wider range of dates. As events become less frequent, the mean age of mixed-regime surface hearths tends to increase, but the variability decreases as the number of exposing events is fewer. However, in all cases, the upper quartile age of surface hearths falls within the last 400 years, showing that the modeled surface archaeological record is biased toward the present as a result of differential preservation.

Variants that have inverse erosion to deposition ratios (e.g., 0.3 and 0.7) feature more or less identical distributions. This is because under more erosional conditions, older hearths are less likely to survive destruction, and thus the record is mostly younger, while under more depositional conditions, older hearths will be hidden by layers of sediment, with only the most recent hearths being visible on the surface. Surfaces featuring similar distributions of hearth ages may have formed under highly divergent geomorphological regimes.

As the length of intervals between geomorphic events increases, chronological gaps appear. Because erosion or deposition events affect all grid cells in the model, all hearths sitting on the surface at those times (which includes all hearths
Figure 4. Distributions of radiocarbon (black) and OSL (gray) data from simulations (A–C) compared with data recorded from Rutherfords Creek (D). A–C, Individual graphs showing samples of 100 dates for each proxy taken from 1,000 separate simulation runs, ordered youngest to oldest, while each graph set shows different surface stability settings ($A = 0$, $B = 0.1$, $C = 0.5$). D, Dots showing mean ages for 93 radiocarbon determinations and a random sample of 93 OSL determinations less than 2000 BP (bars = 1 SD).
accumulated since the last event) will either be obscured by deposition or destroyed by erosion, leaving only hearths from previous intervals exposed on the surface to be joined by hearths from the upcoming interval. Repeating this process produces interdigitating sets of surfaces containing hearths grouped by alternating time periods, with older hearths within those groups becoming rarer through time. If ages were obtained from these surfaces at any given point in time, there would appear to be chronological gaps in the record, but these would be purely the result of geomorphic activity.

Figure 4B and 4C shows the results when surface stability is introduced, simulated as the probability of a cell’s surface remaining stable through an erosion or depositional event. In this simulation, the erosion probability is set to 0.5 with the event interval set to 100 years, but the percentages of cells left stable (s) is varied. As the proportion of stable cells increases, the surfaces on which the hearths rest become less organized by the sedimentary process, and the gaps begin to upgrade (s = 0.1; fig. 4B). As surface stability approaches 50% (s = 0.5; fig. 4C), the gaps are completely extinguished, but a record of increasing frequency toward the present remains. When stability reaches 100% (s = 1, not shown in fig. 4), the record undergoes no geomorphic change and thus displays the uniform record of hearth generation.

The qualitative similarities between the modeled data and those obtained from the field are striking. The chronological gaps in the modeled data reflect the vulnerability of charcoal to dispersal through erosion and to sediment deposition that obscures the hearths themselves. However, hearth stones might be expected to show less dispersal than charcoal because they are much larger than charcoal fragments (Fanning and Holdaway 2001), and thus OSL dates obtained from hearth stones should show less evidence for the chronological gaps. We explored this in the hearth simulation model by taking another set of samples that included hearths that were visible but had lost their charcoal and thus were not included in the radiocarbon sample. We have shown that in the more depositional model environments, the radiocarbon and OSL dates track well together as fewer hearths are destroyed (Davies, Holdaway, and Fanning 2015). However, as conditions become more erosional, the curve of the radiocarbon data remains steeper than that obtained from the OSL dates. This is because hearths that have lost their charcoal in erosional events can still be sampled using the OSL method. Meanwhile, hearths that are obscured by overlying sediments are still effectively invisible to both dating techniques. When conditions become completely erosional, the radiocarbon distribution returns to the exponential curvature also seen under the highly depositional settings, but the OSL distribution straightens out, reflecting the actual record of hearth ages produced by the agents. Gaps that are clear in the simulated radiocarbon chronologies under settings with no surface stability are effectively absent from those in the simulated OSL record. A similar pattern is apparent when the actual radiocarbon ages obtained from hearths in Rutherfords Creek are compared to OSL ages obtained from the hearth stones (fig. 4D). Plotting the radiocarbon and OSL ages together shows variation in steepness similar to that predicted by the simulation indicating how erosion has a different effect on charcoal from hearths compared to the hearth stones. The chronological gaps that are visible in the radiocarbon sample are almost absent in the OSL sample.

Discussion

Hearths in Western New South Wales

To some degree the term “hearth” is evocative. In Western societies, we imagine people sitting around a fire as a center of domestic activity (e.g., Wrangham et al. 1999). This is unlikely to be the type of activity that occurred around the hearths we find in Rutherfords Creek. As heat-retainer ovens, they represent an aspect of food preparation but not one that acted as a focus for domestic activity. The ethnographic accounts cited above indicate that animals prepared and placed in an oven might be left for several hours while the people responsible undertook tasks elsewhere. In contrast, fires used in domestic locations for heat and light tended to be small and were made as needed (Gould 1971). The explorer Sturt, commenting about Aboriginal hearths on the central Darling River, stated, “Our fires were always so much larger than those made by themselves, that, they fancied, perhaps we were going to roast them” (Sturt 1834:150). A heat-retainer hearth might be in use for a considerable period, but it did not need to be tended. Therefore, the location where many daily tasks were carried out need not be the location where the hearth remains are found. While a great many hearths exist, and many more have likely been buried or destroyed, these do not cluster either spatially or temporally into groups that reflect prolonged occupations. Aboriginal people were able to construct hearths throughout the Rutherfords Creek valley, indicating that at different times, there was sufficient fuel and material for hearth stones readily available. From our observations (Fanning, Holdaway, and Pipps 2009), stone was likely sourced from the immediate vicinity of the hearth location. In a small number of cases, termite mound clay was also used as a heat retainer. The locations selected for hearth construction also contained suitable sediments for the excavation of shallow depressions with the technology that they had available. Aboriginal people were also able to access fire in the different locations where the hearths were constructed. Gould (1971) describes the technique he observed for making fire during his time in the Western Desert in the 1960s involving friction when a wooden spear thrower or throwing stick was rubbed across another piece of wood. He cites other accounts where fire was produced by a stick drill and stone percussion, and he recounts how at times fire was carried using a substantial stick or bark (see also Hallam 1975:44). Whether or not these or other methods were employed in the past, the spatially extensive record of hearths that we observed in Rutherfords Creek attests to material availability as well as the technical ability to make and transport fire. Finally, that so
many hearths are distributed so widely also indicates that suitable food items for cooking were available and that the impetus to cook them struck in a range of different locations at different times.

At some level, this wide distribution of hearths in time and space indicates mobility rather than repetitive place use. Our work on portable stone artifacts from Rutherfords Creek as well as other locations in western NSW similarly illustrates how Aboriginal people curated flakes, leaving behind concentrations of artifacts that are in a sense the antithesis of occupation sites (e.g., Douglass et al. 2008; Douglass et al. 2015; Holdaway, Douglass, and Phillipps 2015; Holdaway and Douglass 2015). The artifacts that remain for us to study are those that were not selected for transport because they were considered unsuitable (Holdaway and Douglass 2012). Thus, as Isaac (1983) long ago illustrated by way of a cartoon of an archaeologist imagining a group of hominins sitting around a fire, we have to be wary of deriving social or behavioral explanations from what appear to be self-evident features of the archaeological record.

At larger spatial scales, geomorphic processes affect the abundance of resources available for Aboriginal people to exploit (Holdaway et al. 2015). On the one hand, western NSW illustrates a lack of topographic complexity, with small areas of relatively high topographic roughness bounded by large areas where there is little or no change in relief. On the other hand, there is a high degree of local landscape heterogeneity, a product of modern vegetation cover plus regolith variation. To the degree that this heterogeneity can be used as a proxy for past environmental resource abundance, it suggests that at a local level, resources were likely to be highly variable. In western NSW, resource heterogeneity did not translate into the formation of regularly recurring resource patches largely as a consequence of low soil fertility combined with the rainfall variability (Holdaway, Douglass, and Fanning 2013).

Low fertility and intermittent rainfall produces a landscape that varies both spatially but also temporally in ways that would have been difficult to predict. For humans, this meant that a location rich in resources at one moment in time might become depleted at another, with little way of predicting when such a change might occur. Individual resource patch locations in western NSW were neither continuously nor cyclically attractive for occupation (Holdaway, Douglass, and Fanning 2013). If resources were episodic in their availability, both spatially and temporally, it might be expected that many places would see at least some use and therefore would see the creation of an archaeological record. Periods after episodic, abundant rainfall might lead to enhanced resource availability over large regions; however, at these times more than adequate resources might be available at more places than the available population could exploit at one time. In such a situation, no one place would be significantly better than another. Using a “dots on map” approach, the landscape would appear to be covered by a carpet of occupation debris just as we see in the distribution of hearths in Rutherfords Creek, as though all places were used at once. However, as the results of the analyses discussed above show, the opposite is the case: this carpet of dots is better explained by the high mobility of small numbers of people in a landscape where the ecology and topography leads to the wide dispersal of the archaeological material remains (Holdaway and Fanning 2014).

Taking all these factors into account, the distribution of hearths in western NSW makes sense. Hearths are distributed throughout the valley because at different times, different places might be attractive for hearth construction. At these times, places had sufficient fuel and stones to allow for hearth construction as well as suitable food stuffs to cook. However, while hearths were places where food was cooked, they might not be the places where other activities were concentrated. Because of the unpredictability of resource availability, people needed to be able to access different places at different times, something that we characterize as a low redundancy in place use (Holdaway and Fanning 2014). The same processes that explain the distribution of hearths also have an effect on their preservation and therefore the chronology that can be obtained from the datable materials found with the hearths. Patterns in the chronological distribution of hearth radiocarbon ages may be an outcome of differential dispersal of charcoal and the visibility of the hearths that retain these charcoal deposits. Visibility also has an effect on the hearth chronology obtained with OSL, although in a different way from that using charcoal; differential visibility and hearth erosion means that there are more hearths with recent ages than those that are older using both dating systems, but gaps in the chronological record are most apparent when only the radiocarbon record is viewed.

The simulation study results show how temporal hearth patterns can emerge when hearths are produced consistently and the frequency and likelihood of sediment erosion and deposition are varied. Erosion in Rutherfords Creek was at times spatially extensive. Using hearths dated to the last 2,000 years from all observed clusters, the distribution of radiocarbon ages shows a pattern of fluctuating hearth frequencies similar to that produced in the simulation when the level of surface stability is kept low and sedimentary events are infrequent (Davies, Holdaway, and Fanning 2015). This suggests that something like the alternating effects of erosion and deposition as modeled may be having an effect on hearth distribution, an inference further bolstered by additional patterns in the OSL data predicted by the model (fig. 4D). Modern-day rain events can result in erosion or burial of hearths (Fanning, Holdaway, and Rhodes 2007), and stratigraphic disconformities indicate that at times in the past, considerable volumes of sediment were eroded from valley floor fills (Fanning and Holdaway 2001). Correlations exist between the abundance of hearth ages and past continental scale environmental shifts (Holdaway et al. 2010). These studies indicate the likely mechanisms responsible for the exposure, erosion, reburial, and destruction of hearths in Rutherfords Creek. The hearths visible in the eroded valley floor sediments result from the intersection of all these processes. The interaction between Aboriginal people, the technological forms of fire control they utilized, and the environment explains why they made
hearth features that dominate the discussion of fire use, for what purposes, and in what contexts. Here the implications of the detailed case study presented above need to be considered. With some caveats, the case for the presence of human-controlled fire can be made if suitable features are present, but the case for its absence is much harder to demonstrate (Gowlett and Wrangham 2013). A great deal of research has concentrated on determining the makeup of the hearths themselves, involving ethnographic accounts (e.g., Black and Thoms 2014; Mallol et al. 2007; Thoms 2008), experimental studies (e.g., Broard et al. 2015; Graesch et al. 2014; Homsey 2009; March et al. 2014), and micromorphological studies of likely hearth features (e.g., Aldeias et al. 2012; Berna and Goldberg 2007; Friesem, Zaidner, and Shahack-Goss 2014; Goldberg et al. 2012; Mentzer 2014). However, much less attention has been given to studying the distribution and visibility of hearth features at a landscape scale. Based on the NSW study, we could modify Gowlett and Wrangham’s (2013:10) statement that “Hearth are the most valuable archaeological indicator of fire use, but may be a small part of a general picture in which fire was also exploited on landscapes” to read “fire use in occupation sites may be only a small part of a general picture of hearth use in landscapes.” Those landscape studies that do exist often seek behavioral explanations for hearth distribution, frequency, and age and typically only consider geomorphic explanations to assess whether concentrations of heat-fractured rocks are anthropogenic in origin (e.g., Black and Thoms 2014; Schaefer et al. 2014; Sullivan et al. 2001).

The hearths studied in western NSW were probably not related to domestic activity as such. What we call heat-retainer hearths represent a cooking technology that, given their locations, the nature of the environment, and the types of stone artifacts with which they are spatially associated, signals something other than domestic camps. Thus, the hearths distributed throughout the valley floor do not fall easily into the categories of fire features that dominate the discussion of fire use within Paleolithic archaeological sites (e.g., Berna and Goldberg 2007; Sandgathe et al. 2011; Wadley 2012), nor do they fit within the gamut of broadcast fires used to modify the environment (Scherjon et al. 2015). Instead, they reflect an alternative way in which people in the past could use controlled fire (e.g., Milburn, Doan, and Huckabee 2009; Thoms 2008), apparent only if suitable locations in landscapes amenable to the use of this form of fire technology are investigated. Based on our studies of hearths and stone artifacts, the hearths in western NSW are consistent with people who practiced high levels of mobility. We therefore need to tread carefully when assuming that fire use will fall into the categories that we expect from our own experience or from simple archaeological divisions such as “on site” and “off site” that envisage movement to and from central places of occupation or indeed from limited readings of the ethnographic record involving only domestic fire features associated with these occupations. Absence of fire should not be concluded when consideration is limited to such a small number of categories within a small range of spatial locations. This observation has relevance to interpretations of sites in Europe during the period 0.8–0.5 Ma that preserve large quantities of bone, none of which are charred. For some, this reflects the absence of fire, but as Gowlett and Wrangham (2013) note, the absence of evidence may alternatively indicate that fire was used in places that almost never survive. They note, for example, how fire at Beeches Pit in eastern Britain was used near a water edge. Other similar locations exist in Africa (they note Flindersbad), but in the main, evidence for fires in Europe comes from caves. In these contexts, fires are more extensive during the Middle Paleolithic, although not continuously so in some sites (Sandgathe et al. 2011). What may have changed was the locations where fires were created and therefore the probability of their survival in the archaeological record.

The Australian example also emphasizes the need to consider nonhuman, proxy-specific formation processes when considering evidence of absence. The fire record in western NSW is extensive, but it is probably patterned as a result of differential preservation and visibility. The erosion system that is likely responsible for preservation did not exist in all places and times during the Paleolithic or any other period and place (although of course we would not exclude the possibility that such a system operated at particular times and places). However, the example underlines how we should not assume that the archaeological record is patterned by human behavior alone. To test whether human behavior is indeed responsible for archaeological patterning, we need to employ approaches using a neutral model similar to that illustrated here. To better understand the mechanisms that lead to the presence and absence of hearths and also their apparent increase through time in the Australian record, the use of models needs to be combined with observations made from multiple locations so that the extent and nature of the processes involved in forming the archaeological record can be understood. This cannot be achieved by studying the record from one locality because absence at any one period from such a place could be due to the interaction of multiple processes operating at different scales, many of them natural rather than cultural. Indeed, as we demonstrate, “ab-
sence” can even vary depending on what dating system is used. That a neutral model of hearth construction can produce patterns homologous to the empirical archaeological record from a late Holocene context should be of concern to those analyzing records from the deep past where the accumulated effect of combined formation processes has the potential to be so much greater.

The early records of fire control seem to be very discontinuous through time, leading some to propose that fire use was either not required or intermittent (e.g., Roebroeks and Villa 2011; Sandgathe et al. 2011). From a formation perspective, such an intermittent record may speak of issues connected with preservation and visibility more than it does with the nature of human behavior. Petraglia (2002) reviews the use of what he terms “thermally altered stone,” here referred to as heat retainers, providing case studies from mid-Atlantic Holocene sites in North America. All three of the sites he discusses are on terraces where plowing has revealed the thermally altered rock. Petraglia (2002) comments that western European Middle Paleolithic sites show limited evidence for heat retainers compared with those in the eastern United States, with much greater levels seen only from the Early Upper Paleolithic. He also comments on the lack of thermally altered stones in the earlier Paleolithic sites in open-air locations. This could represent an evolutionary change in the use of fire technology, but it could equally reflect changes in land-use strategies and ensuing changes in the availability of fuel and stone as well as food sources and shifts in the nature of contexts that preserve material from the past. It is the combination of such changes that needs to be considered when assessing the absence of evidence as well as the first appearance of fire use, for example, the appearance of fire use after 400 Ka in Europe discussed above. As the Australian example shows, all these aspects are interconnected, so we should not simply compare the presence and absence of fire features from different time periods and places as though they are equivalent. Comparisons need to acknowledge the potential complexity of hunter-gatherer behaviors no matter what the time period involved and recognize that what we see archaeologically are windows into settlement systems that were likely spatially extensive, as Binford (1983) long ago observed. However, how settlement systems are manifest also probably depends on the geomorphic processes, as the current study suggests. A great deal of attention in the literature is given to analyzing evidence that shows the presence of fire features. The results of this study suggest we should be giving equal attention to understanding, as Gwilt and Wrangham (2013) have recently argued, what the absence of such features might mean. This involves considering a wide range of evidence that, ironically, may seem unconnected (at least directly) to the human use of fire. It also means beginning with a model of formation that does not assume the primacy of human behavior. While this may seem contrary to the anthropological study of early human behavior, we will always run the risk of identifying false negatives without understanding the wider systems in which fire operated and that are involved in the preservation of the archaeological record of fire use. We await the result of such studies with interest.

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Researching the Nature of Fire at 1.5 Mya on the Site of FxJj20 AB, Koobi Fora, Kenya, Using High-Resolution Spatial Analysis and FTIR Spectrometry

by Sarah Hlubik, Francesco Berna, Craig Feibel, David Braun, and John W. K. Harris

Some scholars explain the major anatomical characteristics that differentiate Homo erectus from its predecessor, Homo habilis, as the result of Homo erectus being adapted to use fire for cooking and other tasks. However, many scholars contend that the evidence of fire in Homo erectus sites is very scant and is not convincingly anthropogenic. This study presents a methodology to evaluate the evidence of fire associated with the 1.5-million-year-old Homo erectus site FxJj20 AB, Koobi Fora, Kenya. The evidence is in the form of thermally altered lithics, soil aggregates, and bone fragments identified using visual inspection and Fourier transform infrared spectroscopy (FTIR). We conducted high-resolution excavation focused on the recovery and high-resolution mapping of large and small finds (< 2 cm). ArcGIS spatial analysis and soil micromorphology were used to assess whether the evidence of fire at the site has a natural or anthropogenic origin. Preliminary results indicate that the spatial pattern of heated and unheated archaeological material is not inconsistent with prehistoric anthropogenic fire features found in archaeological sites of Europe and West Asia.

Several studies show fairly convincingly that modern humans depend physically and biologically on the controlled use of fire (Carmody and Wrangham 2009; Wrangham and Carmody 2010; Wrangham and Conklin-Brittain 2003; Wrangham et al. 1999). However, the timing of the initial use of fire by hominins is contentious at best (James 1989; Sandgathe 2017; Sandgathe et al. 2011). Some scholars hypothesize that the dependence on fire use has deep roots in the Homo lineage (Wrangham 2017). Morphological changes (larger body and brain, smaller teeth and gut) in Homo erectus beginning around 2.0 Mya suggest that major changes in feeding strategies such as cooking or other food processing behaviors began at or before this time (Aiello and Wells 2002; Aiello and Wheeler 1995; Organ et al. 2011). While an increase in meat eating (fat and protein) would have provided a greater number of valuable calories (e.g., Blumenschine and Pobiner 2007; Milton 1999; Speth 1989), without hunting to ensure continuous access to fresh meat resources, hominins would have been subject to toxins and pathogens that develop in spoiling meat (Ragir, Rosenberg, and Tierno 2000; Smith et al. 2015). Using fire to cook meat and vegetal foods would have reduced their potential toxicity and, most importantly, increased the caloric return of these foods. This would reduce the amount of metabolic energy needed for digestion by diminishing chewing time and by breaking down complex starches and proteins into more efficiently digestible compounds (Carmody and Wrangham 2009; Wrangham and Conklin-Brittain 2003; Wrangham et al. 1999). Evidence for acquisition of meat resources dates to at least 2.6 Mya (Semaw et al. 2003) and potentially as early as 3.4 Mya (McPherron et al. 2010), while persistent carnivory is shown in the record beginning about 2.0 Mya (Ferraro et al. 2013). The gap between in-
including some meat in the diet and persistent carnivory indicates that some barrier existed to the incorporation of meat in the hominin diet before 2 Mya. It is possible that the acquisition of the use of fire in the behavioral repertoire of hominins was responsible for this. To test this hypothesis, we must establish whether the use of fire, in some capacity, is present in the Early Pleistocene archaeological record associated with H. erectus or H. habilis.

In this paper we illustrate the nature of the 1.5 Mya evidence for fire at the site of FxJj20 AB, located in Koobi Fora, Kenya. The study includes high-resolution mapping and spatial analysis, soil micromorphology, and Fourier transform infrared spectroscopy (FTIR) characterization of the archaeological record. We carefully examine the nature of fire evidence and its distribution and relation to hominin activities to determine whether there is a statistically significant association between the spatial distribution of fire evidence and evidence of other human activities (e.g., flint knapping or butchery). We recognize the difficulty of claiming that ancient hominins controlled fire at 1.5 Mya in the absence of numerous sites with similar patterns. Nevertheless, the work presented here represents a fundamental data point and, more importantly, a methodological benchmark for the investigation of the nature of fire evidence in Early Pleistocene open-air sites of Africa and Eurasia.

Background

Archaeological research in Europe and Southwestern Asia shows that control and maintenance of fire begins sometime in the middle to late Middle Paleolithic (Roebroeks and Villa 2011; Shimelmitz et al. 2014; Sorensen, Roebroeks, and van Gijn 2014). Qesem Cave, Israel, contains evidence of habitual human activities (e.g., flint knapping or butchery). We recognize the difficulty of claiming that ancient hominins controlled fire at 1.5 Mya in the absence of numerous sites with similar patterns. Nevertheless, the work presented here represents a fundamental data point and, more importantly, a methodological benchmark for the investigation of the nature of fire evidence in Early Pleistocene open-air sites of Africa and Eurasia.

Researchers at Gesher Benot Ya’akov (GBY) found a number of burned microartifacts (artifacts <2 cm in maximum dimension) clustered together, while macroartifacts (artifacts ≥2 cm in maximum dimension) were found mostly unburned and away from the burned microartifacts (Alperson-Afl 2017; Alperson-Afl and Goren-Inbar 2010; Goren-Inbar et al. 2004). The researchers proposed that this pattern mirrored the toss and drop zones proposed by Binford (1983). Macroscopic components of the purported hearths at GBY no longer remained intact, but the pattern of burned and unburned artifacts was preserved and used to pinpoint their original locations (Alperson-Afl, Richter, and Goren-Inbar 2007). The site provides strongly suggestive evidence for the controlled use of fire at 780 kya even in the absence of commonly used proxies such as microscopic wood ash and/or burned sediment.

Wonderwerk Cave contains evidence of fire in Acheulean contexts dating back to ca. 1 Mya (Berna et al. 2012). Micromorphological investigation showed the presence of centimeter-thick intact paleosurfaces containing calcified and ashed plant remains (Berna et al. 2012; Goldberg, Berna, and Chazan 2015; Thibodeau 2016). The microscopic evidence, combined with evidence of bone burned at temperatures above 400°C and ironstone manuports with characteristic potlid fractures (resulting from the exposure to high heat), suggests that hominins using Wonderwerk Cave were using fire in some capacity (Berna et al. 2012).

The Koobi Fora FxJj20 site complex spurred the debate over fire use by early hominins soon after the original excavations of all three sites in 1972 and 1973. The sites FxJj20 East and FxJj20 Main were subsequently excavated in the 1970s and into the 1980s as more finds were discovered (Harris 1997). During excavations at FxJj20 East and FxJj20 Main, discrete concentrations of rubified sediment aggregates were found throughout the site (Bellomo and Kean 1997; Harris 1978, 1997). It was proposed that these concentrations were the remains of ancient fires, and subsequent analysis using magnetometry, thermoluminescence (TL; Bellomo 1994; Bellomo and Kean 1997), and phytoliths (Rowlett 2000) indicated that these may instead be related to fire. Spatial analysis of the materials recovered during the excavation (Bellomo 1994) indicated that stone tool and bone concentrations were closely associated with the rubified sediment concentrations, further indicating that these patches may be the result of fire associated with hominin activities.

Earlier excavations at the FxJj20 sites did not have the advantage of modern technology to aid in mapping and were not
undertaken with a methodology focused on the recovery of small finds. Artifacts and bone were plotted by hand and smaller (<2 cm in maximum dimension) artifacts and bone were recovered in the screen. While items recovered in the screen are useful for many analyses, such as lithic technology and faunal lists, these materials are less suitable for high-resolution spatial analysis as imprecise placement can skew analyses. Since the original excavations at the FxJj20 sites, advancements in recovery and analysis techniques have enhanced the ability to identify hominin fire use (Berna and Goldberg 2007; Goldberg and Berna 2010; McPherron and Dibble 2002). Recovery of all possible artifacts, piece plotted with the aid of a total station, make it possible to map even the smallest artifacts, ecofacts, samples, and feature boundaries with millimeter accuracy (McPherron and Dibble 2002). Soil micromorphological techniques coupled with FTIR microscopy allow for the identification of microscopic fire evidence such as wood ash, burned bone, burned soil, or microcharcoal (Berna et al. 2012; Berna and Goldberg 2007; Goldberg and Berna 2010). The use of portable FTIR allows for the identification of burned materials in the field or lab (Berna and Goldberg 2007; Weiner 2010). Spatial analysis using advanced geographical information systems enable the identification and visualization of density-related patterns (Anselin and Getis 1992; Henry 2011).

Using methods such as soil micromorphology, FTIR, magnetic susceptibility, paleomagnetism, and TL (Berna and Goldberg 2007; Goldberg, Miller, and Mentzer 2017; Shahack-Gross, Bar-Yosef, and Weiner 1997), fire itself is relatively easy to detect in the archaeological record. Wildfire evidence is described as diffuse and irregular (Gowlett et al. 2017), and recent paleoenvironmental studies show that with expansion of grasslands, the East Africa landscapes became progressively fire prone at the beginning of the Pleistocene (Magill, Ashley, and Freeman 2013), so the probability that wildfire affected the remains of prehistoric camps is higher in East Africa than in other geographic regions. Conversely, anthropogenic fire at base camps or in living spaces in the Early Pleistocene should be distinguishable as fairly localized evidence of fire closely associated with artifacts. Thus, to be able to distinguish between wildfire and human-made fire, it is fundamental to produce high-resolution maps of heated and not heated macro- and microscopic artifacts and ecofacts. Evidence of exotic fuel brought to the site and fire-starting techniques (e.g., pyrite, marcasite, tin-

### Table 1. List of sites before 400 kya with evidence of fire

<table>
<thead>
<tr>
<th>Location</th>
<th>Period</th>
<th>Evidence of fire</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Africa:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koobi Fora, FxJj20, Kenya</td>
<td>1.5–1.6 Mya</td>
<td>Burned lithics, reddened sediment</td>
</tr>
<tr>
<td>Chosowanja, Gji16/6E, Kenya</td>
<td>1.42 Mya</td>
<td>Reddened sediment</td>
</tr>
<tr>
<td>Gadeb, Ethiopia</td>
<td>0.7–1.5 Mya</td>
<td>Burned lithics</td>
</tr>
<tr>
<td>Swartkrans, South Africa</td>
<td>1.0 Mya</td>
<td>Burned bones</td>
</tr>
<tr>
<td>Wonderwerk, South Africa</td>
<td>1.0 Mya</td>
<td>Ash, charcoal, burned bone</td>
</tr>
<tr>
<td><strong>Southwest Asia:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gesher Benot Ya’aqov, Israel</td>
<td>780 kya</td>
<td>Burned lithics, charcoal, burned seeds</td>
</tr>
<tr>
<td>Qesem Cave, Israel</td>
<td>400–200 kya</td>
<td>Hearths, ash, burned bone</td>
</tr>
<tr>
<td>Tabun, Israel</td>
<td>350 kya</td>
<td>Hearth, ash, phytoliths</td>
</tr>
<tr>
<td>Hayonim, Israel</td>
<td>250–100 kya</td>
<td>Ash, charcoal, phytoliths</td>
</tr>
<tr>
<td><strong>Europe:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atapuerca, Spain</td>
<td>1.2–780 Mya</td>
<td>Dispersed charcoal</td>
</tr>
<tr>
<td>Isernia, Italy</td>
<td>606 kya</td>
<td>Burned bone, burned sediment</td>
</tr>
<tr>
<td>Boxgrove, England</td>
<td>MIS 13</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Highlodge, England</td>
<td>MIS 13</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Beeches Pit, England</td>
<td>MIS 11</td>
<td>Burned lithics, burned bone, burned sediment, hearth</td>
</tr>
<tr>
<td>Verteszöllös, Hungary</td>
<td>MIS 9–11</td>
<td>Burned bone, hearth</td>
</tr>
<tr>
<td>Blitzingluben, Germany</td>
<td>MIS 9–11</td>
<td>Charcoal, burned lithics, burned bone</td>
</tr>
<tr>
<td>Terra Amata, France</td>
<td>380–239 kya</td>
<td>Charcoal, burned lithics, burned bone, hearth</td>
</tr>
<tr>
<td>Orgnac, France</td>
<td>MIS 9–8</td>
<td>Burned bone, ash</td>
</tr>
<tr>
<td>Petit Bost, France</td>
<td>MIS 9/8</td>
<td>burned lithics</td>
</tr>
</tbody>
</table>

* Clark and Harris 1985.
* Brain 1993.
* Gibbon et al. 2014.
* Berna et al. 2012.
* Alperson-Afil and Goren-Inbar 2010.
* Shahack-Gross et al. 2014.
* Albert et al. 1999.
* Roebroeks and Villa 2011.
* Preece et al. 2006.
der fragments) can be used to assess the anthropogenic origin of fire, especially if found in close association with evidence of human activities such as stone tools or butchered animal bone. All individual pieces of evidence need to be evaluated within the larger context of the site itself and in reference to other evidence found.

Material and Methods

FxJj20 AB Site

All three FxJj20 sites are located on weakly lithified, fine-grained, floodplain tuffaceous silts (Harris 1997). The site of FxJj20 AB, discovered in 1973, is located about 150 m north-east of the FxJj20 East and FxJj20 Main sites (fig. 1). The artifacts and bone appear to be deposited on a gentle (~5°) east to west slope. A small 16 m² test excavation was undertaken, and excavator notes describe recovering reddened clasts in the screen, though none were recorded in situ. The 1970s excavation resulted in a collection of lithics (n = 2,626) that are clearly the result of intentional flaking, often showing flake scars, but preserving no bulbs of percussion or platforms (Harris 1997).

In 2010, we resumed excavations at FxJj20 AB and expanded the site by 24 m² to the east and north of the original excavation. We hoped to detect discrete, consolidated concentrations of reddened sediment similar to those found at FxJj20 East and FxJj20 Main (J. W. K. Harris, FxJj20 site notes, 1973). Such concentrations were not found, but a preliminary spatial analysis of the artifacts found at the site identified “Locus 1,” a circular, low-density area surrounded by a higher-density concentration in the northeast portion of the site (fig. 2). The artifacts making up a large concentration around Locus 1 are primarily smaller than 2 cm in maximum dimension (henceforth “microartifacts”), while a larger concentration of larger artifacts (>2 cm in maximum dimension) were recovered farther to the west of the largest concentration of microartifacts. As all the surrounding squares had been excavated to the same elevation as the square containing Locus 1 and small artifacts as well as bone fragments surrounded Locus 1, we hypothesized that Locus 1 might be the location of a fire feature. On this assumption, we have continued excavation and sampling of the site to resolve this question.

Excavation Methods at FxJj20 AB Site

Between 2010 and 2015, 24 squares were excavated to the depth of the artifact-bearing layers, nine of which were further excavated to sterile layers. One was left unexcavated to serve as a stratigraphic reference and allow for micromorphology sample collection to document any microscopic stratigraphic features.
The excavation of FxJj20 AB is designed to document the three-dimensional locational data of as many artifacts as possible, particularly microartifacts. Dental tools and paintbrushes are the primary excavation tools; sediments are removed in 5 cm levels. Spatial data are recovered using a total station and handheld data collector running EDM Mobile (McPherron and Dibble 2011). Obviously elongated artifacts are shot using two shots on the long axis to determine artifact orientation and help understand site formation processes (McPherron 2005). Sediment is screened through a 2 mm mesh screen to ensure recovery of small artifacts and ecofacts. Recovered materials are classified and recorded (see supplemental material online for details). With this methodology we collect three-dimensional coordinates for ~95% of the recovered material, allowing high-resolution spatial analysis of the materials and enabling us to make predictions about activities on the site.

**Soil Micromorphology**

Soil micromorphology analysis was performed to characterize the sediments at the microscopic scale and reconstruct the history of local sedimentological processes. Several intact sediment blocks were collected throughout the site, following Stoops (2003) and Goldberg and Macphail (2006), to examine the entire stratigraphic sequence and features observable in the field. Intact sediment blocks were pedestalied in situ and wrapped with plaster of paris strips. The top and north-south orientations were recorded on the blocks before removal. Labeled plastered blocks were cut out of the excavation and rewrapped with more plaster of paris and packing tape to ensure sample integrity during transportation and shipment to the lab. In the lab, blocks were air-dried at 50°C, embedded in styrene-diluted polyester resin under vacuum, cured, and cut into 2 × 3 inch and 1 × 2 inch blocks (chips). The chips were prepared into petrographic thin-section slides by Spectrum Petrographics (Vancouver, WA). The thin-section slides were analyzed by petrographic microscopy with an Olympus BX41 following the criteria in Stoops (2003) and by FTIR microscopy using a Thermo-Nicolet iN10 MX FTIR microscope (see below). The petrographic thin-section slides were examined for composition and micromorphological features to identify remains of paleosurfaces, human activities, and natural processes (i.e., bioturbation and pedogenesis).
**Heat Experiments**

Over the course of several seasons (2012–2015) we conducted a number of heat experiments to build a reference collection of heated sediment, bone, and local lithic raw materials. We investigated various lithologies, including Gombe and Asille basalt. Gombe basalt makes up approximately 50% of the artifacts found at Fxjl20 Main (Braun, Harris, and Maina 2009). These heat experiments were conducted in the lab and in the field to document visible heat-related changes (e.g., discoloration, fractures) and mineralogical transformations using FTIR (see below). Experimental work in the geoarchaeology lab at Simon Fraser University (SFU) included firing sediment samples (taken from the center of Fxjl20 AB), Gombe basalt, and Asille basalt in a muffle furnace (ThermoLyne 30400) at 400°C, 550°C, and 800°C for four hours. Field experiments placed tested materials in camp fires fueled with wood locally available at Koobi Fora. Experimentally heated materials included cobbles and flakes of basalt, ignimbrite, chert, and chalcedony, all of which would have locally available to hominins in the past. An infrared thermometer was used to measure the temperature of the experimental camp fires; all fires reached temperatures above 550°C and lasted at least 6 hours. We visually inspected heated raw materials in the field at Koobi Fora Base Camp, at the National Museums of Kenya (N Mk) in Nairobi, Kenya, and at the SFU lab. FTIR testing of unheated and heated materials was performed with a portable FTIR spectrometer (Thermo-Nicolet iS5) at the NMK in Nairobi and at the SFU geoarchaeology lab. Laboratory experiments of the basalt and subsequent FTIR testing are still ongoing; thus, the results presented here are considered to be preliminary.

**FTIR Spectrometry and Microspectrometry**

FTIR spectrometry has been used extensively to characterize the organic and inorganic composition of archaeological materials, features, and deposits (Weiner 2010), and in particular to identify heated materials in the archaeological record (Berna and Goldberg 2007; Berna et al. 2012; Shahack-Gross, Bar-Yosef, and Weiner 1997; Shahack-Gross et al. 2014; Weiner 2010; Weiner et al. 2015). FTIR spectrometry makes it possible to recognize heat-induced mineralogical transformation in bone, chert, calcite, and clay minerals (Berna 2010; Berna et al. 2007, 2012; Berna and Goldberg 2007; Shahack-Gross, Bar-Yosef, and Weiner 1997, 2014; Weiner et al. 2015). Micro-destructive FTIR sampling (milligram particles) was conducted on archaeologically collected bulk and single-grain sediment samples, discolored aggregates, and bone and lithic fragments as well as unheated and experimentally heated local sediment and lithic raw materials. Initial FTIR analysis was conducted at the NMK, Nairobi, Kenya, at the close of the 2015 field season. Further testing took place at the SFU lab. We ground samples with an agate mortar and pestle, mixed them with potassium bromide (KBr), and pressed them into pellets using a hand press (Pike Technologies). The pellets were analyzed using a Thermo-Nicolet iS5 spectrometer collecting 64 scans in the 4,000 to 400 cm⁻¹ wavenumbers with a resolution of 4 cm⁻¹ wavenumbers.

All materials (soil particles, bone fragments, lithic raw material flakes, and pebbles) recovered from within Locus 1 (location of a potential combustion feature) were analyzed by FTIR to test for indications of heating. Materials from throughout the site were tested by FTIR spectrometry to look for other heated items and identify potential natural or anthropogenic combustion features. When burned material was identified, lithics and bone fragments collected from its proximity were also tested. Testing on random samples of bone and stone from throughout the site was also conducted.

A Thermo-Nicolet iN10 MX FTIR imaging microscope was used to analyze petrographic thin sections. Spectra of particles with diameter of 50 to 150 μm were collected in transmission and total reflectance modes with a Reflectocromat 15 μm objective between 4,000 cm⁻¹ and 450 cm⁻¹ at 8 cm⁻¹ resolution.

**Spatial Analysis**

Spatial analysis was performed using ArcGIS on stone artifacts, bone fragments, and rubified sediment aggregates recovered with three-dimensional coordinates. Materials recovered in the screen (less than 5% of the material recovered during the 2010–2015 excavations) were excluded from the spatial analysis.

Vertical and horizontal spatial distribution of artifacts gives insight into the stratigraphic makeup of the site. Analysis of the vertical distribution of the artifacts coupled with the soil micromorphological analysis may shed light on whether the archaeological assemblage derived from a single occupation or a palimpsest of many occupations (Bailey 2007; Malinsky-Buller, Hovers, and Marder 2011).

Optimized hot spot analysis. ArcGIS-optimized hot spot analysis (OHSA) uses the Global Morans I statistic to calculate statistically significant clusters, or “hot spots,” within a specified geographical area. Unlike kernel-density estimates, which will run with any sample size, OHSA requires a minimum number of data points to work. When performed with the spatial analysis software ArcGIS (ESRI), OHSA aggregates data within polygons. When no specific bounding polygon is identified, the analysis uses a predefined fishnet grid over the site, and empty polygons are discarded from the analysis. If a bounding polygon is defined, empty polygons within the boundary are included in the analysis. The analysis can run with or without a weighting field. Weighting data can be any type of data on which results are evaluated, such as population numbers in a city or number of cases of disease. Without a weighting field, the analysis calculates spa-
tial similarity alone. With a weighting field, the analysis calculates spatial similarity in relation to the weighted field.

For this analysis, OHSAs were run with and without weighting. For all analyses, a 10 cm grid was overlaid on the site. For the weighted analysis, maximum dimension of artifacts was used. Densities of larger materials should be identified as “hot spots,” while densities of smaller materials will be identified as “cold spots.” This method obviates the need to classify materials as micro- or macroartifacts and provides a more accurate method of grouping materials according to size. The analysis will show whether artifacts in a spatial cluster are similarly sized.

The OSHA will define areas on the site where there is significant clustering and also determine whether materials on the site cluster according to size. We expect that if material is clustering on the site, this will show up in the OSHA. If there are no clusters on the site, the analysis will return nonsignificant results.

Toss and drop zones and ring distribution. Analyses of toss and drop zones, as proposed by Binford (1983), have taken several forms. They are used to identify the potential location of hearths where fire evidence such as ash and charcoal are absent (Alperson-Afil 2017; Alperson-Afil, Richter, and Goren-Inbar 2007; Sergant, Crombé, and Perdaen 2006; Vaquero and Pastó 2001), but they are also used to look at activities that may have occurred around known hearths (Henry 2012; Stappert 1989). While clusters of artifacts on a site can be useful to define the potential location of a combustion feature, this information should be corroborated by the presence of burned material. Potential toss and drop zones are identified by looking at the spatial distribution of bone and lithic materials on a site coupled with an analysis of artifact size. As Binford (1983) directly noted around modern ethnographic campfires, smaller pieces of stone or bone (unintentionally produced waste) should be found in the drop zone, directly in front of the individual working with these items. Larger pieces (intentionally discarded waste) should be found in the toss zone, which can be expected to be found up to several meters distance behind, to the side, or in front of the individual (Binford 1983). Binford (1983) cites similar distributions patterns around hearths observed by John Yellen in the Kalahari and Richard Gould in Australia. A comparable pattern is observable in the distribution of burned archaeological materials at GBY (Alperson-Afil 2017; Alperson-Afil and Goren-Inbar 2006, 2010; Alperson-Afil, Richter, and Goren-Inbar 2007; Goren-Inbar et al. 2004). If an activity area associated with fire is present, we expect small materials, or debitage, to be clustered together (i.e., drop zone), while larger materials will be found farther out and clustered separately from small materials. We would expect large lithic tools, hammerstones, and flakes to cluster away from small debitage on the site.

Henry (2012), in a study of the Middle Paleolithic site of Tor Faraj, showed several potential configurations of the toss and drop zones that can be distinguished by the distribution of archaeologically recovered materials around a fire. Modeling his research after Stappert’s (1989) work at Pincevent, Henry (2012) proposed that around 120 cm from the fire there would be a drop in numbers representing the “squat zone,” the place where an individual would sit or squat to work around the fire. He developed three hearthside ring profiles to describe the activities on a site. In his analysis, he looked at the frequencies of materials up to 2 m from the center of the hearths found on the site (Henry 2012). He defined three observable patterns: Type I, toss-zone dominant, where the majority of artifacts are found behind the individual working around the hearth; Type II, drop-zone dominant, where some materials are found in the toss zone immediately behind the individual but most are found in the drop zone in front of the individual; and Type III, drop-zone dominant, where nearly all the material is found in front of the individual (Henry 2012). For Types I and II, Henry (2012) defines a “squat zone” where the individual working around the fire would be sitting and suggests that maintenance of the work area is responsible for these patterns. He suggests that the Type III pattern indicates that an individual did not move from his or her workspace and did not try to maintain a clear workspace (Henry 2012). These analyses do not take size into account, only frequency of artifacts from the center of the hearth. Comparisons between distributions from Tor Faraj, Jordan (Henry 2012), Pincevent, France (Stappert 1989), and FxJj20 AB were made using a Kolmogorov-Smirnov test to determine whether the material from FxJj20 AB fits the patterns found at other Middle and Upper Paleolithic sites. If the profile of materials from FxJj20 AB matches one of the ring profiles proposed by Henry (2012), we can hypothesize that it derived from behavior associated with a hearth.

Results

Excavation (Artifacts and Site Formation)

The number of artifacts recovered in situ from all excavated areas at FxJj20 AB totals 2,969 objects (table 2). The distribution of recovered materials is given in figure 2. The vertical spread of artifacts is between 8 cm in the lowest-density areas to 20 cm in the highest-density areas, with a maximum spread of 40 cm at the eastern edge of the excavation (fig. S1; figs. S1–S9 available online). The distribution of all materials recovered from the site shows a high density of artifacts spreading from the center to the northeastern portion of the site. A cross-sectional view of the excavation shows that the archaeological material is found on a slight (~5°) slope following the natural topography of the area (see fig. S1). Large and small finds are distributed throughout the excavation. There is no preferred orientation of the artifacts, indicating that no postdepositional transport of materials occurred (see Hlubík et al. 2017 for details on orientation studies). Lithics from the excavation retain sharp edges and do not show any other signs of transport and redeposition by water (fig. 3). Furthermore, there is a large...
The proportion of small objects (40% have a maximum dimension less than 2 cm) that would be affected by significant hydraulic action (Schick 1986). The numbers of artifacts found within each size class from the new (2010–2015) excavations at FxJj20 AB are consistent with those recorded by Schick (1986) from knapping experiments before winnowing treatments (fig. S2; Hlubik et al. 2017). While some identifiable pieces of bone were found during the 1970s–1980s excavation, most taxonomic identifications were made from tooth fragments that included representative species of the families Bovidae, Suidae, Equidae, Rhinocerotidae, Hippopotamidae, Cercopithecidae, Hystrixidae, Chelonia, Aves, and Thryonomyidae (Harris 1997). Much of the faunal evidence found during the 2010–2015 excavations is extremely fragmentary and not identifiable beyond "mammal," "reptile," or "fish" categories. Some are identifiable to general element (e.g., "long bone"), but most are small fragments between 1 cm and 5 cm in maximum dimension and are identifiable only as "bone." Cortical surfaces are largely missing, making it difficult to determine whether butchery was occurring at the site. Faunal analysis is ongoing to determine the total portion of identifiable fauna, whether any fragments refit, and whether more specific elemental and taxonomic determinations can be made. Aggregates of rubified sediment are found throughout the site, with the highest concentrations in the central and southern portion of the site and much lower densities in the northern portions (fig. S3). It is important to note that there are several low-artifact-density areas in the site, but one particular area (Locus 1) is located in the middle of several high-density clusters of objects. All squares adjacent to Locus 1 were excavated and had significant artifact densities. Approximately one quarter of Locus 1 (~0.7 m in diameter; see fig. 2) was excavated, and while some artifacts and bone were found, the density was much lower than the surrounding areas. However, a number of ru-

Table 2. List of all finds from the excavation at FxJj20 AB

<table>
<thead>
<tr>
<th>Excavated materials</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone tools:</td>
<td></td>
</tr>
<tr>
<td>Core</td>
<td>85</td>
</tr>
<tr>
<td>Cobbles</td>
<td>16</td>
</tr>
<tr>
<td>Flakes</td>
<td>1,435</td>
</tr>
<tr>
<td>Whole flakes (n = 795)</td>
<td></td>
</tr>
<tr>
<td>Broken flakes (n = 640)</td>
<td></td>
</tr>
<tr>
<td>Flakes with potlid evidence (n = 3)</td>
<td></td>
</tr>
<tr>
<td>Angular fragments</td>
<td>1,372</td>
</tr>
<tr>
<td>Debitage (n = 1,328)</td>
<td></td>
</tr>
<tr>
<td>Potlids (n = 4)</td>
<td></td>
</tr>
<tr>
<td>Pebbles</td>
<td>52</td>
</tr>
<tr>
<td>Hammerstones</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>2,969</td>
</tr>
<tr>
<td>Raw material:</td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>2,807</td>
</tr>
<tr>
<td>Quartz</td>
<td>19</td>
</tr>
<tr>
<td>Ignimbrite</td>
<td>60</td>
</tr>
<tr>
<td>Chert</td>
<td>58</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>21</td>
</tr>
<tr>
<td>Feldspar</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>2,969</td>
</tr>
<tr>
<td>Fauna:</td>
<td></td>
</tr>
<tr>
<td>Bone</td>
<td>1,242</td>
</tr>
<tr>
<td>Tooth</td>
<td>102</td>
</tr>
<tr>
<td>Total</td>
<td>4,313</td>
</tr>
</tbody>
</table>

Figure 3. Left, photographs of some artifacts from the FxJj20 excavations. The artifacts are fresh, not rolled, and show no signs of being transported in or by water. Right, photograph of an example of a potlid identified through lithic analysis; ventral side (far right) is irregular with no signs of a bulb of percussion. A color version of this figure is available online.
bifid sediment aggregates \((n = 18)\) were recorded but not collected from Locus 1.

**Soil Micromorphology**

Micromorphological analysis of the excavated area shows that the sediment is locally composed of very weakly pedogenized tuff with feldspathic, micaceous, and quartz silt to fine sand (fig. 4a). These sediment characteristics indicate that the archaeological material was deposited on a low-energy, rapidly aggrading surface such as should be expected on an active floodplain. The porosity of the sedimentary column consists of a few subcentimeter-size root channels and rare larger passage features and other fabric pedofeatures. Limpid laminated yellow clay coatings (fig. 4b) suggest postdepositional, low-energy, subsurface translocation of clay formed from the weathering of the tuff. Interestingly, no calcium carbonate crystalitic b-fabric or pedofeatures have been observed in any of the thin sections analyzed. Evidence of soil mixing appears to be limited to grass roots, arthropods, and earthworm action. There is no evidence of major bioturbation from tree roots or by vertebrates such as rodents or reptiles. It is likely, given the fine-grained nature of the sediments, the small size of the artifacts, and the lack of features produced by strong or prolonged pedogenesis, that the accumulation of sediment at the site was the result of seasonal or decadal flooding events from a nearby channel. The exact location of the channel has not yet been pinpointed (Harris 1997). Micromorphological analysis shows that the sediment of Locus 1 has the same general composition and structure of the adjacent areas. It differs slightly because of the presence of rare rubberized soil aggregates and a slightly higher content of fine sand (fig. 4c). No evidence of wood ash or bone fragments has

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**Figure 4. Soil micromorphology at FxJj20 AB.**

- **a.** Plane polarized light (left) and cross polarized light (right) scan of petrographic thin sections of intact block of local soil column, catalog no. 25015 (scale bar = 1 cm). Note the silty clay loam texture, channel microstructure, and a few passage features (p.f.).
- **b.** Representative cross polarized light micrograph of the local ground mass (scale bar = 200 µm). Note the micaceous, feldspathic, and quartz composition of the poorly sorted silt and sand and the laminated clay coatings around pores and sand grains.
- **c.** Plane polarized light (left) and cross polarized light (right) scan of petrographic thin sections of intact block from inside Locus 1 (scale bar = 1 cm). Note sediment has similar composition and structure with respect to local sediment shown in figure 5b (sample catalog no. 25015) and contains rare rubberized soil aggregates (r.a.). A color version of this figure is available online.
been found in the blocks sampled so far from Locus 1 or other areas.

**Experimental Work and Archaeological Evidence of Burning**

Upon being heated, Gombe and Asille basalt specimens did not exhibit a color change, but large pieces exposed directly to fire often spalled in convex subrounded flakes (aka potlids), sometimes reducing an entire cobble through the process and producing thousands of rock fragments. These potlids lack striking platforms or bulbs of percussion (fig. 3) and are distinguishable from flakes produced by knapping activities. During the firing experiments, the potlids projected out of the fire, sometimes to a distance of several meters. Experimental potlids generally have an irregular surface texture that contrasts with the smoother texture observed on debitage flakes derived from stone knapping. Smaller flaked pieces of basalt sometimes sustained potlid fractures but more often emerged from the fire unchanged. Forty-four archaeological specimens of basalt were identified as potlids through comparison with experimentally produced potlids and debitage. The 44 archaeological potlids are found scattered throughout the site and are plotted in figure 2. This kind of spatial distribution is expected because potlids can be ejected several meters from the fire. The incidence of numerous potlids on the site indicates the presence of fire, but it is not expected to indicate the exact location of the fire.

One piece of reddened chert was found roughly 3 cm to the southeast of the edge of Locus 1. The chert from FxJj20 AB is generally a yellow-brown color. This reddened chert retained some of the original brown color along one edge, but over 90% of the piece is a deep red color. The reddening of the piece is similar to the heat-induced discoloration observed in other chert samples (which had similar coloration before heating) and thus is considered to be burned (Purdy and Brooks 1971).

Unheated and heated samples of the two principal local raw materials, Gombe and Asille basalts, were analyzed by FTIR. Gombe and Asille basalts have overall similar FTIR spectra. Gombe basalt shows a unique hydroxyl absorption at ca. 3,620 cm⁻¹, assigned to weathered olivine. Upon heating Gombe basalt to 500°C, the FTIR absorption at 3,620 cm⁻¹ is lost (fig. S4). Although it would be possible to use FTIR to distinguish between unheated and heated Gombe Basalt, unfortunately the FTIR patterns of unheated and heated Asille basalts and heated Gombe basalt are statistically indistinguishable (fig. S4). Thus, we do not consider FTIR alone to be a reliable method for unequivocally distinguishing between burned and unburned Gombe and Asille basalts.

Experimental lab work showed that when sediment from the site was heated, it underwent a dramatic color change from a light grayish tan to a deep red color (fig. 5b). This color change was incremental according to temperature, with the material burned at 400°C turning only slightly red and the material burned at 800°C turning a deep red. FTIR analysis also shows clear spectral differences between the unburned and burned sediments with temperature-dependent pattern characteristics (fig. 5b).

Over 600 pieces of bone, 170 pieces of rock, and 24 samples of discolored sediment were tested using FTIR. Of these, 50 pieces of bone and five samples (one in situ) of rubified sediment were found to show evidence of being heated. Of the materials found within Locus 1, one bone fragment had FTIR absorptions characteristic of being burned above 500°C and below 700°C (Berna 2010; fig. 5a). One sample of rubified sediment, found approximately 1 m east of Locus 1, was identified using FTIR as being burned. Around this, six pieces of bone were identified as burned (fig. 2). An additional 43 bone specimens from other areas of the site were identified as burned.

**Spatial Analysis**

Spatial analysis shows distinctive clusters of material on the site, both horizontally and vertically. The results of individual analyses are discussed below.

**OHSA.** Horizontally, the artifacts occur in one large dominant cluster in the northeastern portion of the site (fig. S5) with several smaller clusters to the southeast. The OHSA identified the large cluster as significantly different from a random distribution at a 99% confidence level (fig. S5). Overall the clusters are composed of similarly sized materials (fig. S6). Significant clusters of artifacts >2 cm are shown in red, while significant clusters of artifacts <2 cm are shown in blue. Areas with no distinctive clustering of certain size-class specimens are indicated with cream-colored circles—these clusters contain materials that fit into both large and small categories.

Specimens of bone tend to be found in clusters that overlap with the concentrations of stone material, particularly the smaller artifacts (fig. 5). Clustering of artifacts and bone are highest around Locus 1: smaller artifacts cluster primarily to the west and southwest, bone clusters primarily to the south and west as well but wraps around to the north, and larger artifacts cluster to the west of Locus 1. The small cluster of materials to the northeast of Locus 1 is primarily made up of artifacts that are both large and small.

One aggregate of rubified sediment was recovered within Locus 1, and more are found dispersed throughout the central and southern portions of the excavation site. A small group of burned material (potlids, bone, sediment aggregates) is found to the west of Locus 1 and constitutes a statistically significant cluster of burned materials, which could be thus considered the location of a contained fire.

**Toss and drop zones and ring distributions.** The spatial distribution around Locus 1 is compatible with that of combustion features identified using the toss- and drop-zones analysis (Binford 1980, 1983). Specifically, smaller materials are found close to Locus 1, along with high concentrations.
of bone, while larger materials are found more distant from Locus 1. Histograms showing the distribution of artifacts throughout the entire site (fig. S7) show the highest concentrations of artifacts are adjacent to Locus 1. The ring distribution of the materials from around Locus 1 shows that the greatest numbers of materials are found between 80 and 120 cm from the center of Locus 1 (figs. S8C, S9B). Type III hearths are not maintained in the same way as Type I and II hearths, but the ground immediately around the knapper is likely to have a lower density than the surrounding area. Potential squat zones for FxJj20 AB are labeled on figure S5.

Another potential locus of fire activity is the area defined by the highest concentration of burned material (Locus 2, fig. 2). Using the center of the polygon describing the cluster of burned material, we measured the distribution of artifacts in concentric rings from this polygon. A comparison of these ring distributions to Floor 3 (hearths 10 and 13) at Tor Faraj, Jordan, and TI12 at Pincevent, France (figs. S8D, S9C), shows that the FxJj20 AB Locus 2 assemblage is comparable to these three archaeological hearths. Kolmogorov-Smirnov tests show that the sample from FxJj20 AB is consistent with the distributions found at Tor Faraj (Locus 1 and H10 and 13, P = .97; center of burned cluster and H10, P = .97; and center of burned cluster and H13, P = .99) and at Pincevent (Locus 1, P = .88; center of the burned material, P = .99). These Upper and Middle Paleolithic hearths are classified as unimodal Type III.

Figure 5. a, FTIR spectrum of bone sample 12400 showing absorption at ca. 565, 603, 630, 960, 1,040, 1,090, 1,415, 1,455, and 3,570 cm⁻¹ characteristic of bone carbonate hydroxyapatite heated to ca. 550°C (Berna 2010). b, FTIR spectra of unheated (bottom pattern) and experimentally heated FxJj20 AB sediment to 400°C, 550°C, and 800°C. Note the weak absorptions at 915, 3,625, and 3,695 cm⁻¹ of kaolinite in the unheated sediment that disappear upon heating the sample to 400°C. Also note the shift of the major Si-O band from 1,026 to 1,089 cm⁻¹ upon the incremental heating of the sediment. A color version of this figure is available online.
drop-zone dominant hearths, which bear resemblance to the ring profile at FxJj20 AB.

Discussion

The meticulous recovery, high-resolution mapping, and analysis of the archaeological materials found at FxJj20 AB suggest that the site has undergone weak postdepositional disturbance. None of the current analyses indicate deflation or artifact winnowing by hydraulic action. Soil micromorphy analysis suggests the site is part of a fairly rapidly aggrading deposit, with sediments brought onto the site by low-energy water. While without refit studies we cannot rule out a palimpsest of overlapping occupations, the vertical distribution is within the range of refitting artifacts at FxJj50 (vertical dispersion at FxJj50 is 10–50 cm), a similar site in floodplain deposits located a few kilometers from FxJj20 AB (Bunn et al. 1980; Kroll 1994). The soil micromorphological analysis revealed small root and invertebrate action and minimal disturbance by larger bioturbation agents. The greatest spread in vertical distribution coincides with the high-density concentration of small (<2 cm) artifacts, which could be explained by small root action disturbing and displacing these artifacts. At FxJj50, Kroll determined, through refitting studies, that the material accumulated there was probably the result of one or a few occupations on a single surface before burial rather than multiple accumulations on several surfaces overprinting each other and intermixing (Kroll 1994). The small size of the artifacts at FxJj20 AB makes refitting studies difficult, but these are planned for the future to help resolve the question of whether the site is a single accumulation or a palimpsest of a number of accumulations on a rapidly aggrading surface.

The clustering of materials at FxJj20 AB provides some insights into hominin activities. The high proportion of flake debitage and broken or damaged flakes suggests that much of the flint-knapping activities occurred on the site. Comparison to the experimental data reported in Schick (1986) indicates that the site is probably a site where flint-knapping activities took place (i.e., a primary production site). The mixture of lithic artifacts and bone fragments is not inconsistent with an unspecialized camp, possibly a camp where individuals brought resources together for processing. The distribution of materials suggests the site may extend farther to the east, and future excavations will shed light on the total extent of the site.

FTIR analysis shows that five rubified sediment aggregates and at least 50 pieces of bone were heated to or above 500°C. Furthermore, while now there is no established morphological definition of a potlidity fracture, and the size and shape will likely vary with material type, analysis of the lithics at the site has identified a number of flakes that, based on comparison to experimental examples, are very likely potlids resulting from basalt objects being exposed to fire. Given the presence of potlids and FTIR-determined heated bone and sediment, it is reasonable to consider the other rubified sediment aggregates to be heated, but at temperatures below 500°C. The limited number of heated bone fragments and sediment (0.014% of total material recovered) indicates that burning may have happened in discrete patches and was not widespread across the site, as a wildfire would have been.

More testing of materials found on the site will allow us to make a more definitive determination about the extent of fire on the site and the thermal history of the basalts found there. Additional analysis of the sedimentological samples, both by FTIR and magnetic techniques, may be able to further clarify the extent and nature of fire at FxJj20 AB.

At the moment we have identified two main locations where fire may have been localized: Locus 1 and Locus 2 (figs. 2, S3). Locus 1 is the low-artifact-density area located immediately east and north of the highest density of materials found on site and immediately southwest of a second high-density cluster. We propose that Locus 1 may be the location of an ancient fire because of the lack of artifacts and the presence of burned bone found within this circular area and reddened chert adjacent to it. Moreover, small materials dominate the high-density cluster west of Locus 1. This is compatible with the phenomena of “drop zones” as described by Binford (1983). The highest density of these specimens is found within 120–140 cm of the center of Locus 1 (fig. S7). The minimal overlap between large and small materials found on the site is consistent with the tass and drop profiles around hearths proposed by Binford (1983) and comparable to a similar distribution described for Middle and Upper Paleolithic combustion features (Alpersen-Afil, Richter, and Goren-Inbar 2007; Henry et al. 1996; Sergant, Crombè, and Perdaen 2006; Vaquero and Pastó 2001). The distribution profile matches the unimodal Type III, drop-zone-dominant profile identified by Henry (2012; fig. S8), and the presence of burned materials within Locus 1 at the center of this distribution further supports the hypothesis that the behavioral signal found on the site may be the result of fire-control behavior by the hominins using the site. The lack of microscopic calcitic wood ash in Locus 1 deposit is explained with ethnographic analogues and the local soil conditions that do not favor calcium carbonate formation and preservation. Mallol et al. (2007) demonstrated that in several open-air Hadza combustion features, even in some long-lasting ones, the amount of wood ash that is incorporated in the subsoil is surprisingly low. The general absence of calcium carbonate components and pedofeatures in the FxJj20 AB soil suggests that processes that result in calcium carbonate being leached away from the top and subsoil horizons dominate the soil environment.

The second potential location of fire (Locus 2) corresponds to the area defined by the greatest density of artifacts and burned materials. This area is where burned sediment from the site is found in conjunction with the majority of the burned bone. The position of Locus 2 to the west of Locus 1 (fig. S6) suggests that Locus 2 corresponds to a combustion feature subsequent to a Locus 1 combustion feature. The distribution of Locus 2 artifacts is consistent with ring profiles previously described for other prehistoric hearth features. A comparison of a ring profile centered on a polygon describing the highest
density of burned materials (fig. S9) shows no significant difference between the ring profile centered here and the hearth features described at Tor Faraj (Henry 2012) or Pincevent (Stappert 1989; fig. S9). Locus 2 is consistent with a fire location because of the high volume of burned materials found here. However, it is of some concern that the majority of materials found here are not burned, as would be expected for a localized fire. The mixed composition could be the result of material being moved around by animals or hominins or the result of a rapidly aggregating palimpsest site. More study of the micromorphology of the site, refitting studies, and statistical spatial analysis may shed light on postdeposition processes on the site.

Future plans include the institution of a field-based microwe territory laboratory to facilitate experimental and archaeological investigations for microscopic charcoal and phytolith residues found in Pleistocene archaeological contexts. None-}

Acknowledgments

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References Cited


Our work demonstrates that a recovery strategy designed to retrieve and map as much burned and unburned archaeological material as possible coupled with high-resolution spatial analysis has great potential to provide important information on the nature of the association of the archaeological record with fire in primary contexts of great antiquity.

References Cited


Conclusion

The integration of techniques such as soil micromorphology, FTIR, and spatial analysis allowed the identification and precise contextualization of heated archaeological materials (lithics, bone, and sediment) in the 1.5 Mya old Early Stone Age context at FxJ20 AB, Koobi Fora, Kenya. We have come to the following conclusions. (1) Spatial analysis reveals statistically significant clusters of ecofacts and artifacts, indicating that the archaeological material is in situ and is probably the result of various hominin activities during one or a few occupation phases over a short period of time. (2) We have found evidence of fire associated with Early Stone Age archaeological material in the form of heated basalt (potlids flakes), heated chert, heated bone, and heated rubbed sediment. To our knowledge this is, to date, the earliest securely documented evidence of fire in the archaeological context. (3) Spatial analysis shows the presence of two potential fire loci. Both loci contain a few heated items and are characterized by surrounding artifact distributions with strong similarities to the toss and drop zones and ring distribution patterns described for ethnographic and prehistoric hearths (Binford 1983; Henry 2012; Stappert 1998).

In summary, our results confirm the presence of fire in the Early Stone Age context of Koobi Fora FxJ20 previously documented by Harris (J. W. K. Harris, FxJ20 site notes, 1973, 1997). In addition, our findings at FxJ20 AB support the hypothesis of a close association of fire residues with hominin activities. To test the hypothesis of an anthropogenic origin of the fire at FxJ20 AB, more intensive sampling for FTIR, soil micromorphology, and other microscopic remains such as microdebitage, microcharcoal, and phytoliths is needed. In fact, our work demonstrates that a recovery strategy designed to retrieve and map as much burned and unburned archaeological material as possible coupled with high-resolution spatial analysis has great potential to provide important information on the nature of the association of the archaeological record with fire in primary contexts of great antiquity.


Spatial Analysis of Fire
Archaeological Approach to Recognizing Early Fire

by Nira Alperson-Afil

The use of fire by early hominins is considered a significant technological and cultural revolution. Recently, the study of fire use has been affected by troublesome trends that views chemical and microscopic techniques as the only acceptable analyses of fire residues, thus ignoring basic archaeological observations and analyses. This paper discusses the diverse expressions of early fire, their variability, and their level of significance and suggests that the spatial analysis of burned residues is a reliable method for recognizing early fire. Evidence from the site of Gesher Benot Ya’aqov (GBY) suggests that fire was routinely used by Acheulian hominins. In addition, new data on the spatial association between percussive activities and fire are presented. Such evidence of routine and habitual use of fire requires intensity and recurrence, documented in sites with long occupational sequences such as GBY. This requirement excludes habitual use of fire from the majority of early hominin habitations, documented by short-term occupations of open-air sites. To deny Early to Middle Pleistocene hominins of the habitual use of fire is to ignore the archaeological record of their evolution, behavior, and culture.

Identifying Prehistoric Fire

In the early years of prehistoric research, an archaeological association between stone tools and burned materials was considered an adequate indication for the use of fire (e.g., Garrod and Bate 1937). Later, issues of depositional integrity and the probability of natural fires were considered, adding refinement to the association between human activities and burned residues. At present, even that relationship is deemed insufficient, and some scholars consider the presence or absence of a hearth (fireplace) the sole criterion for proving fire use (e.g., Shahack-Gross et al. 2014), preferably with the support of a microcontextual approach (Goldberg, Miller, and Mentzer 2017). This is of prime importance, as hearths are often not preserved archaeologically, and their absence is thus wrongly interpreted as lack of evidence.

Hearths are features of all contemporary hunter-gatherer societies, and ethnographic data suggest that open hearths, which involve no construction, are more common than hearths comprising dug pits, stone or wood linings, or a structure of some sort. In addition, when found, ethnographically or archaeologically, hearths exhibit high variability of construction method, size, and function (Galanidou 1997; Mallol and Henry 2017; Mallol et al. 2007), and this variability increases when they are exposed and excavated at archaeological sites. In his Dictionnaire de la préhistoire, Leroi-Gourhan suggested that a hearth will exhibit discoloration (dark sediments) and that charcoal should be preserved (Leroi-Gourhan 1988:405). Schiegl et al. (1996) suggest another definition that similarly depends on the state of preservation: “Good field evidence for the use of fire is the presence of well-preserved hearths. Such hearths are usually

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round or oval shaped and often have an upper layer composed of light coloured minerals, a lower layer rich in charcoal, and a substrate of reddened sediment” (Schiefl et al. 1996:763–764). These descriptions, however, appear to suit the definition of a “well-preserved hearth” better than that of a “hearth.” The ethnogeoearchaeological study of Mallol et al. (2007) demonstrated that the preservation of combustion features is not a straightforward issue, particularly in open-air sites: “the anthropogenic signature of open air combustion structures can be detected depending on the rates of sedimentation and the impact of postdepositional disturbance factors. . . . If the rates of sedimentation are low, leading to erosion, the remains of an ephemeral open air fire are likely to disappear” (Mallol et al. 2007:2050). Similarly, discoloration of sediments around and beneath the hearth depends on a variety of factors (e.g., fuel used, soil moisture, chemical variations in sediments) and requires favorable depositional and postdepositional conditions in order to be preserved in the archaeological record (Bellomo and Harris 1990; Canti and Linford 2000; Linford and Canti 2001). Thus, as preservation depends on age and soil chemistry, among other things, it is evident that the definition of a hearth varies in terms of sedimentological setting, intensity, size, fuel used, structure, and function. These variables will eventually dictate the archaeological appearance of these features, that is, whether hearths will exhibit a stone lining, whether ash and/or charcoal will be preserved, or whether discoloration of the sediments will occur. Consequently, as in the ethnographic record, the archaeological occurrences of hearths are extremely variable and uneven, and hearths are independently defined for each site.

The only common feature of all hearths is the simple fact that people intentionally burn fuel in order to produce a fire. Accordingly, the archaeological definition of a hearth should specify that it is an anthropogenic combustion area variable in structure, size, and depth that preserves the remains of burned materials. We should bear this in mind when reviewing interpretations of early evidence of fire use, as they often lack comprehension of this variability. The variability of evidence is further complicated by certain lines of evidence that are bound to be absent in sites in which postdepositional processes have concealed the evidence: “taphonomic problems related to the preservation of ash . . . charcoal, . . . and other indications of fire use . . . hinder the discovery and recognition of burnt remains” (Karkanas et al. 2007:198). These taphonomic complexities constrain the attempts to identify early human use of fire and actually suggest that of the various possible methods, spatial analysis of burned residues is the most accessible and efficient, particularly when a durable component such as lithics is concerned.

Spatial Analysis

A broad definition of spatial analysis was provided by Clarke (1977), who perceived spatial archaeology as “the retrieval of information from archaeological spatial relationships and the study of the spatial consequences of former hominid activity patterns within and between features and structures and their articulation within sites, site systems and their environments” (Clarke 1977:9). Two main approaches can be distinguished among spatial analysis studies that focus on a single site (intratise). The first involves studies that investigate the formation of archaeological spatial patterns in actualistic contexts—ethnographic or experimental—aiming to provide models for the formation of archaeologically observed spatial patterns (e.g., Binford, Kroll, and Bunn 1991; Binford 1968, 1978; O’Connell, Hawkes, and Jones 1991). The second approach is using a variety of methods for analysis of archaeological spatial patterns, including the recognition and interpretation of similarities and differences in distribution among artifacts and features, mapping of the excavated area, identifying clusters of artifacts, refitting of lithics and bones, etc., and these methods are often assisted by different spatial analysis software.

The behavioral implications of spatial analysis studies are straightforward; that is, the remains of human activities are distributed nonrandomly because human behavior is not random across space. This derives from the behavior of our species for which the segregation of activities is a means to organize and manipulate cultural environments and to codify social relationships (e.g., Binford 1978, 1983, 2001; Galanidou 2000; Gargett and Hayden 1991; O’Connell 1987; Yellen 1977).

Clearly, before attempting to spatially analyze archaeological remains, their spatial integrity should be established. A variety of postdepositional and taphonomic processes may have altered the original spatial configuration of the archaeological material. In addition, any spatial analysis should follow clear stratigraphic observations, reassuring that a distinct occupation is under analysis rather than palimpsests of several occupations (e.g., cave sites).

Spatial Analysis and Fire

The fact that humans tend to carry out a vast range of activities in close proximity to hearths is widely documented. The hearth assembles the social group, and around it is the area in which social interactions, tool production, food processing, food consumption, and ritual ceremonies are carried out (Binford 1983, 1998; Brooks and Yellen 1987; Galanidou 1997, 2000; Spurling and Hayden 1984; Yellen 1977). While numerous activities leave no tangible evidence for us to uncover (e.g., social interactions), other activities (e.g., tool making and food processing) contribute directly to the formation of the archaeological record. Hearths not only serve as spatial spots of accumulation but also influence the patterns of distribution of certain size groups of the assemblage. Binford (1978, 1983) suggested that the formation of certain spatial patterns during work around a hearth appears to be universal and that the distribution of waste often displays two concentric zones around the hearth: the drop zone in proximity to the hearth, where small fragments of bone/stone are left in situ, and the toss zone, an area farther away from the hearth to which the larger debris is tossed. Thus, the area clo-
est to the hearth is likely to display high quantities of small in situ refuse. Notwithstanding, spatial analysis studies often concentrate on the larger refuse and features despite the fact that “the data most likely to be informative . . . are very small refuse items, such as chipping debris, small bone fragments, and plant macrofossils, which will often be found in primary context” (O’Connell 1987:104). Yet no conventional limit has been defined as a critical size factor for determining what is considered small refuse, which can range from several millimeters (e.g., Dunnell and Stein 1989; Fladmark 1982; Metcalfe and Heath 1990; Stein and Teltscher 1989; Vance 1987) up to several centimeters (DeBoer 1983; O’Connell 1987).

In conclusion, ethnographic observations suggest that the association between features (e.g., hearths) and the spatial distribution of artifacts can provide the contextual framework of artifact concentrations. Consequently, in attempting to reconstruct the formation process of hearth-related spatial patterns, we can draw on the following inferences: a wide range of activities is carried out in close proximity to hearths; hearths are spatial spots of refuse accumulation, and small refuse is more likely than large refuse to be left in situ; hearths are thus likely to display dense concentrations of burned small refuse. Such hearth-related discard patterns have been reported from a variety of archaeological settings, including open-air sites (e.g., Gilead 1980; Gilead and Grigson 1984; Hietala 1983; Leesch et al. 2005; Sergant, Crombe, and Perdaen 2006) as well as rock shelters and cave sites (e.g., Galanidou 1997; Vaquero and Pastó 2001), in all of which the hearths are readily identifiable features. In addition, hearth-related spatial patterning were reported from different cultural settings of varying chronologies. At the Middle Paleolithic occupation at Belvédère, clusters of burned artifacts suggested the presence of hearths (Stapert 1990). The Aurignacian of Abri Castanet (White et al. 2017) presents spatial association between ivory beads and their production debris around the fire features. At the Magdalenian sites of Champréveyres and Monruz in Switzerland, hearths are characterized by various amounts of cobbles, stone slabs, and extremely abundant and well-preserved wood charcoal (Leesch et al. 2005). Regardless of the remarkable preservation of these sites, the spatial distribution of burned flint microartifacts has proved to be the optimal indicator for the precise location of the hearths (Leesch et al. 2005).

Spatial Analysis and Fire at Gesher Benot Ya’aqov

The waterlogged site of GBY is located on the shores of the paleo–Lake Hula in the northern Jordan Valley in the Dead Sea Rift. The Early to Middle Pleistocene sediments document an oscillating freshwater lake and represent some 100,000 years of hominin occupation (OIS 18–20) dating to 790,000 years ago. Fourteen archaeological horizons indicate that Acheulian hominins repeatedly occupied the lake margins, where they skillfully produced stone tools, systematically butchered and exploited animals, gathered plant food, and controlled fire.

The study of fire use at GBY followed the hearth-related spatial patterning discussed above. Our basic assumption was that clusters of debris, specifically small burned debris, are indicators of the locations of hearths, defined as “phantom hearths”—features that lack other observable traits (e.g., structuring, discoloration of sediments, ash, or charcoal). Leroi-Gourhan’s definition of structures latentes established the approach to such archaeological features, namely, that these can be discernible through observable patterns of artifacts’ spatial distributions (Leroi-Gourhan and Brézillon 1972). These principles guided the study of fire use at GBY, where large amounts of small knapping waste products were recorded within the archaeological layers (table 1). These include flint microartifacts (2–20 mm in length) and macroartifacts (longer than 20 mm) recovered during excavation and through postexcavation sorting of the wet-sieved sediments. Experimental studies have dem-

Table 1. Area, volume, and counts of lithic artifacts in the levels of Layer II-6 from the topmost layer of the stratigraphic sequence (younger) to the lowermost (older)

<table>
<thead>
<tr>
<th>Level</th>
<th>Areaa</th>
<th>Volumeb</th>
<th>Unburned flint</th>
<th>Burned flint</th>
<th>Basalt</th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;2 cm</td>
<td>≤2 cm</td>
<td>&gt;2 cm</td>
<td>≤2 cm</td>
<td>&gt;2 cm</td>
<td>≤2 cm</td>
</tr>
<tr>
<td>L-1</td>
<td>23.79</td>
<td>4.28</td>
<td>1,192</td>
<td>53,081</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-2</td>
<td>25.62</td>
<td>3.07</td>
<td>496</td>
<td>73,064</td>
<td>16</td>
<td>877</td>
</tr>
<tr>
<td>L-3</td>
<td>17.92</td>
<td>2.50</td>
<td>494</td>
<td>91,050</td>
<td>16</td>
<td>563</td>
</tr>
<tr>
<td>L-4</td>
<td>16.64</td>
<td>2.16</td>
<td>635</td>
<td>105,022</td>
<td>16</td>
<td>1,406</td>
</tr>
<tr>
<td>L-4b</td>
<td>13.69</td>
<td>0.82</td>
<td>151</td>
<td>7,182</td>
<td>5</td>
<td>443</td>
</tr>
<tr>
<td>L-5</td>
<td>13.39</td>
<td>1.20</td>
<td>186</td>
<td>31,862</td>
<td>12</td>
<td>1,211</td>
</tr>
<tr>
<td>L-6</td>
<td>12.62</td>
<td>1.58</td>
<td>325</td>
<td>12,282</td>
<td>9</td>
<td>251</td>
</tr>
<tr>
<td>L-7</td>
<td>12.60</td>
<td>1.38</td>
<td>598</td>
<td>23,457</td>
<td>19</td>
<td>677</td>
</tr>
<tr>
<td>Total</td>
<td>136.27</td>
<td>16.79</td>
<td>4,050</td>
<td>396,998</td>
<td>99</td>
<td>6,182</td>
</tr>
</tbody>
</table>

a Area (in square meters) represents the spatial extent of the excavated material.
b Volume (in cubic meters) is the excavated area multiplied by the estimated mean of excavated thickness based on cross sections.
c Items larger than 2 cm (i.e., macroartifacts: flake tools, cores and core tools, and bifacial tools).
d Smaller items (i.e., microartifacts).
onstrated that direct contact of flint with fire of high temperatures (350°C–500°C) results in distinctive thermal macrofractures (e.g., potlid fractures), which are readily identified (Purdy 1982, 1975; Purdy and Brooks 1971; Sergant, Crombe, and Perdaen 2006). At GBY, the spatial distribution of flint artifacts was examined using spatial analyses software (ESRI ArcMap 9.3), available with the GIS package, in order to detect possible clusters of burned material. Such clusters of burned flint were recorded throughout the entire depositional sequence at GBY. They are relatively small and incorporate both burned and unburned flint microartifacts. Within the kernel of these clusters, the relative percentage of burned flint microartifacts is always higher than that of the unburned ones, and homogeneity analysis indicated that the observed percentages of burned flint microartifacts in the center of these clusters are higher than what we would expect if the distribution of the burning was uniform. In addition, the significance of the statistical tests carried out on the spatial distribution of burned flint microartifacts in each of the studied archaeological levels further substantiates the observed clustering. This extensive study was facilitated by the minimal effect of postdepositional processes on the spatial configuration of the archaeological material (Ashkenazi et al. 2005; Goren-Inbar, Werker, and Feibel 2002; Rabinovich et al. 2012), and its methodology and results were published in detail (Alperson-Afil 2008; Alperson-Afil and Goren-Inbar 2010; Alperson-Afil, Richter, and Goren-Inbar 2007; Goren-Inbar et al. 2004), demonstrating with certainty that the hominins of GBY controlled fire and used it routinely.

Segregating Activities around the Fire at Gesher Benot Ya’aqov

Once the use and control of fire at GBY were established, the option to trace hearth-related spatial patterns became possible. A single occupation level (Level 2), one of eight superimposed occupational levels of Layer II-6, was selected, and its lithic, faunal, and botanical remains were spatially examined (Alperson-Afil et al. 2009). The analyses of Level 2 indicated that hominins carried out different activities in two distinct locations. Abundant knapping took place in the northwestern area, resulting in a dense concentration of unburned flint microartifacts. Other significant aspects of this activity area include the use of chopping tools and fish exploitation, the latter also recorded in the vicinity of the hearth, where greater variation was found in the activities carried out there. While flint knapping around the hearth was less intensive, basalt and limestone knapping was spatially restricted to the hearth, which also served as a focal point for biface modification and for activities involving the use of chopping tools, side scrapers, end scrapers, and awls. In addition, the differential preservation of fish and crabs, along with their spatial distribution, suggests that they were consumed near the hearth (Alperson-Afil et al. 2009). Another hearth-related activity was revealed when the percussors and the pitted stones of Level 2 were spatially ana-lyzed, suggesting that percussive activities (e.g., nut processing) were carried out near the hearth and may have involved the use of fire.

This paper presents new data on the possible association between percussive tools and fire at GBY. The study focuses on the eight superimposed occupational levels of Layer II-6, a sedimentary sequence that represents some 10,000 years of hominin occupation (Craig Feibel, personal communication). The levels of Layer II-6 were rapidly sealed, preserving the original location of different artifacts (evidenced by the preservation state of the lithics, the preservation of mollusk embryos, the presence of conjoinable bones, and a lack of winnowing; see, e.g., Ashkenazi et al. 2010, 2005; Feibel 2001; Goren-Inbar, Werker, and Feibel 2002; Rabinovich et al. 2012).

**Percussive Tools**

Percussive tools are an important component of the lithic assemblages of GBY (Goren-Inbar et al. 2015) and were most

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Figure 1. Basalt percussors. *a*, #16326, Layer II-2/3. *b*, #14887, Layer II-6, Level 3.
likely used by the hominins for stone knapping, nut cracking, and a variety of food-processing activities (both vegetal and faunal). The percussive tools of GBY are modified mostly on basalt unmodified nodules or slabs and include percussors, pitted stones, and thin anvils. The basalt percussors (fig. 1) are rounded nodules, somewhat elongated and usually of cobble size, that present battering or small pitting damage on their surface. Some percussors are shattered as a result of their use in intensive knapping or percussive activity of hard materials. These artifacts show rough and uneven breakage surfaces that lack ventral face features and are classified as split percussors. Thin anvils (fig. 2) are basalt slabs with two flat, parallel, un-flaked surfaces that sometimes bear signs of the heavy percussive force that caused their fragmentation. These anvils have a particular trapezoid geometry, with part of the upper surface occasionally sloping to form an acute angle with the lower surface (Goren-Inbar et al. 2015). Both thin anvils and percussors frequently exhibit pitting damage on their surfaces. Such damage, however, is recorded on a variety of other artifacts, all classified as pitted stones. Pitted stones (fig. 3) are thus either unflaked nodules or slabs or flaked artifacts that bear small pits (depressions) on their surfaces. These pits are often shallow, and their number and location on the surfaces varies. While some pits are organized in clusters of small pits on one of the artifact faces, others are less distinct and seem to resemble battering marks in restricted areas. In most cases the pits occur in the central part of the artifact and rarely on the marginal edges (Goren-Inbar et al. 2015)

Percussive Activities and Fire

The eight sequential levels of Layer II-6 were spatially analyzed in order to explore possible associations between their hearth or hearths and their archaeological material. More specifically, the spatial position of the different types of basalt percussive tools was examined. The results of these analyses are presented in figure 4. Each level is illustrated in two stages; both present

Figure 2. Basalt thin anvils. a, #5255, Layer II-6, Level 1. b, #7695, Layer II-6, Level 6.

Figure 3. Basalt-pitted stones. a, #2312 Layer II-6, Level 1. b, #14177 Layer II-6, Level 2; giant core with a cluster of pits.
Figure 4. Layer II-6, Levels 1–7. *a*. Complete field map superimposed on the kernel density map of burned flint microartifacts. *b*. Assemblage of basalt percussive tools superimposed on the kernel density map of burned flint microartifacts.
the density map of the burned flint microartifacts of the examined level and its association with (a) the map of the archaeological level as drafted in the field and (b) with the basalt percussive tools in their recorded excavated coordinates.

Regardless of the percussive tools, examination of the field maps raises several interesting observations. First, there are clear differences between the occupational levels, probably reflecting different site uses (e.g., elephant butchering in Level 1, biface production in Levels 4 and 4b). And yet despite these differences, fire is present in each of the occupational levels. Interestingly, in many cases (particularly clear in Levels 3 and 6) the artifacts in the field map seem to be positioned in an archlike manner, and their radial configuration looks as if it is surrounding the hearth or hearths (fig. 4).

As for the distribution of percussive tools, the results show that in all occupational levels, the different classes of percussive tools are found in association with each other; thus, where there is an anvil, there are percussors and pitted stones. This may indicate that despite their morphological differences, they were used in similar or related tasks. When present, split percussors are spatially associated with percussors (excluding a single case in Level 5). Most important, the different classes of percussive tools are spatially associated with the hearths, suggesting that percussive activities, probably related to food processing, were carried out in the vicinity of the hearth (fig. 4).

Discussion

Identifying Early Fire with Spatial Analysis Methods

The use of spatial analyses at GBY enabled the identification of phantom hearths and their association with percussive activities throughout the archaeological sequence. Our results illustrate that spatial analysis is an efficient method for identifying early use of fire, particularly at open-air sites where taphonomic conditions often limit the use of chemical and microscopic techniques.

Such sites form the bulk of early hominin occupation areas, and often their evidence for fire use is considered unreliable. Thus, review of the evidence reveals two major pitfalls—the misuse of hearths as exclusive indicators of fire use, and the question of fire use as sporadic versus habitual (Karkanas et al. 2007; Roebroeks and Villa 2011; Shahack-Gross et al. 2014). Hearths are variable features, and their preservation requires particular depositional conditions. Their identification requires rejection of the involvement of natural agents (taphonomic disturbances, natural fires) and the documentation of discrete concentrations of burned residues. Such concentrations can be identified using an array of methods: by the naked eye (e.g., flint, bones, charcoal, ash) and by chemical and microscopic techniques (e.g., bones and sediments). This approach should be just as applicable to early prehistoric sites as it is to sites of modern humans, where burned flints are used to mark the locations of hearths regardless of chemical or microstratigraphic analyses (Sergant, Crombe, and Perdaen 2006).

Where There’s Smoke, There’s Fire

Based on archaeological observations and analysis, fire was used for the first time by hominins in Africa some 1.5 million years ago. Indications are available from cave sites in South Africa (Swartkrans: Brain and Sillen 1988; Pickering 2012; Wonderwerk: Beaumont 2011; Berna et al. 2012) and include burned sediments, bones, and stone artifacts. The use of fire in these two sites is acknowledged by most scholars despite the lack of “hearth” features. Sites in East Africa (e.g., Koobi Fora: Isaac and Harris 1978; Chesowanja: Gowlett et al. 1981) display clusters of burned sediments in a hearth-like arrangement. However, as these are open-air sites that have been affected by taphonomic disturbances, the evidence is considered insufficient by many (but see Hlubik et al. 2017). In Eurasia, the earliest evidence is recorded from GBY, as discussed above. Elsewhere in Eurasia, the use of fire is well attested from 0.4–0.3 Ma, and accumulations of burned sediments, often in conjunction with burned stone artifacts and bones, occur regularly (Garrod and Bate 1937; Gowlett 2006; Karkanas et al. 2007; Vertes and Dobso 1990). At the 0.4 Ma site of Beeches Pit in England, the evidence includes numerous burned flints, bones, shells, and charcoal, and their spatial patterning, including refitting series, is in association with a hearth-like feature (Gowlett 2006; Gowlett et al. 2005). The difficulty is that Europe lacks conclusive evidence for fire use during its early stages of occupation, ca. 1.0–0.8 Ma (e.g., Parfitt et al. 2010). Some explain this gap as an indication that fire was used only sporadically before 0.4 Ma and that it was not an essential element in the subsistence of the first Europeans (Roebroeks and Villa 2011). Rightfully, Gowlett and Wrangham (2013) call for a more mature approach to early fire studies, one that does not ignore the findings of evolutionary, dietary, and social studies, which facilitate a comparative view of early hominin adaptations and behavior.

The concept of habitual use of fire is used to differentiate between an early, sporadic use and a later, controlled, and intensive use. What, however, does sporadic use entail: limited purposes or short duration? Fire was discovered, domesticated, and used by early hominins. Habitual use, however, requires intensity and recurrence of the evidence, as documented in sites with long occupational sequences. This requirement excludes habitual use of fire from the majority of early hominin habitations, documented by short-term occupations of open-air sites. Clearly, along with the advantages that fire brought to hominins, it also made them dependent on its benefits (in diet, technology, social life, and culture) and more and more vulnerable to its loss. To deny Early to Middle Pleistocene hominins of the habitual use of fire (e.g., Sandgathe 2017) is to ignore the archaeological record of their evolution, behavior, and culture.

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Evidence of Hominin Use and Maintenance of Fire at Zhoukoudian

by Xing Gao, Shuangquan Zhang, Yue Zhang, and Fuyou Chen

Evidence for “controlled use of fire” by Homo erectus pekinensis at Zhoukoudian Locality 1 was initially discovered in the early 1930s and was widely accepted as the earliest such record in human evolutionary history for more than half a century. However, since the mid-1980s, this evidence has been questioned. Some of the questions were based on new research results, including geochemical and taphonomic studies conducted in the 1990s. Others are hypothetical and to some extent stem from a theoretical shift in ideas about early hominin subsistence capabilities, including hunting big game and using fire. Limited access to Chinese archaeological collections and literature, limited geological sampling, and postdepositional disturbance might all contribute to the results of these recent investigations. A thorough review of original field notes, excavation reports, and research papers leads to the conclusion that fossils, cultural materials, and traces of fire use in certain horizons at the site are abundant, unambiguous, and mutually supportive. New field investigations and laboratory analyses at Locality 1, ongoing since 2009, have yielded new evidence that indicates that Layer 4 contains clear-cut evidence for in situ use of fire. Future research may well reveal similar evidence for Layers 8–9 and 10, potentially resolving this ongoing debate comprehensively.

Zhoukoudian (ZKD, also Choukoutien or Chou-kou-tien) in early literature) Locality 1, close to Beijing, has been well known since the 1920s because of the discovery of Sinanthropus (Homo erectus pekinensis) fossils, stone artifacts, and evidence of hominin-controlled use of fire (Black 1926, 1931; Pei 1934). Deposits at the site have been divided into 13 stratigraphic layers (fig. 1), with Layer 4 referred to as the “Upper Cultural Horizon” and Layer 8–9 the “Lower Cultural Horizon” (Jia 1959; Pei and Zhang 1985). With respect to the time frame of hominin occupation at the site, fission-track dating was employed in the early 1980s, which determined that the formation of Layer 10 probably took place 462 ± 45 kya while Layer 4 was deposited approximately 299 ± 55 kya (Guo et al. 1980, 1991). Thermoluminescence dating was also applied at the site, generating an age of 417–592 kya for Layer 10 and 292–312 kya for Layer 4 (Pei et al. 1985). Uranium-series (U-series) dating on animal teeth produced an age range of 230–256 kya for Layers 1–3 and an indefinite date of >300 kya for Layer 8 (Zhao et al. 1985b). The detailed chronology of ZKD Locality 1 established by early investigations was reviewed by Zhao et al. (1985a) and Goldberg et al. (2001). Shen et al. (2001) published older ages for key horizons at the site using mass spectrometric U-series dating of intercalated calcite samples: 400 kya for Layers 1–2, 500 kya for the upper part of Layer 5, and 600 kya for the middle and lower parts of Layer 5. In 2009, Shen et al. used 26Al/10Be burial dating to determine the age of the lower component of the deposits (Layers 7–10) yielding an estimate of 770 kya (Shen et al. 2009).

For more than half a century, burned items (including stones, bones, and seeds; fig. 2), charcoal fragments, and “ash accumulations” unearthed from the site had been proposed and generally accepted as the earliest evidence of “controlled use of fire” by early hominins, evidence supplemented by the results of chemical analyses that identified free carbon in the burned fossils and “ash” remnants (Black 1931; Jia and Huang 1984; Oakley 1955; Pei and Zhang 1985; Shen et al. 2004; Wu 1999). Since the mid-1980s, some scholars have questioned the evidence of in situ burning at the site and thus the notion that H. erectus pekinensis had the capability to control fire (e.g., Binford and Ho 1985; Binford and Stone 1986; Boaz et al. 2004; Goldberg et al. 2001; James 1989; Weiner et al. 1998). Considering the new discoveries of evidence for hominin use of fire from even earlier contexts in Israel and South Africa (Berna et al. 2012; Goren-Inbar et al. 2004), the possible signs of fire use at ZKD would no longer constitute the earliest. However, ZKD Locality 1 is still worth further investigation as a case study for Pleistocene hominin adaptation as well as with respect
to the variability and diversity of human behavior in different geographic regions.

Early Research on the Use and Maintenance of Fire at Zhoukoudian

The ZKD site was treated as a fossil vertebrate locality when scientific investigations were initiated there in 1918. In 1929, Pei Wenzhong (also Pei Wen-Chung and W. C. Pei), the ZKD field director at that time, began to pay attention to possible evidence of fire use at the site: mainly charred or partly calcined animal bones (Black 1931). In late 1930, P. Teilhard de Chardin, a principal investigator on the ZKD project, took samples of the apparently burned materials to Paris for comparative studies with similar items found in prehistoric sites in Europe. Chemical analysis of these materials was conducted at the Laboratory of Mineralogy of the Paris Museum. Free carbon was detected, indicating that the blackened antler and mammal bones had indeed been burned. Later, similar analyses were carried out in the Department of Pharmacology of Peking Union Medical College on samples of possible ash and associated charred bone fragments. Once again, the possibility of heavy metal contamination was ruled out, the presence in the sediments of a significant amount of carbon was demonstrated, and a significant free carbon component was confirmed (Black 1931). Based on such analyses and the association of the burned materials with *Homo erectus pekinensis*...
fossils and stone artifacts, Davison Black announced that “It is thus clear beyond reasonable doubt that Sinanthropus knew the use of fire” (Black 1931:108).

According to original field notes and other documentation, evidence of fire use detected in early excavations at ZKD included burned bones, rocks, arboreal (Celtis) seeds, charcoal, and ash. Such remains were recovered from four layers in Locality 1, namely Layer 4–5, Quartz II, Layer 8–9, and the lower horizon of Layer 10. Burned items were often found to have been concentrated in certain spots; in particular, three piles of ash were discovered and recorded in the Gezitang (Pigeon Hall or Chamber of the Pigeons). Two were located conformably on top of a large limestone slab, and some limestone breccia was burned into lime, making the sediments a multicolored mixture of dark red, brown, and white. In some horizons, fine sediments became layers of hard latosol (Pei and Zhang 1985).

Since the time of Black’s announcement, ZKD Locality 1 was widely accepted as preserving the earliest record of the “controlled use of fire” in human prehistory (Movius 1948; Oakley 1956; Zhang 1985). Hallam Movius even provided a vivid description of the way fire was used by H. erectus pekinensis:

Fire was a basic item in his daily life. He presumably cooked his meat over the open hearth in which he burned the wood of the Redbud (Cercis blackii), a type of shrub. Since fire would have provided warmth in the then-existing cave, and since it would keep predatory animals away at night, it must have been an immense asset to him. (Movius 1948:402)

Zhang Senshui (S. S. Chang) summarized perceptions of H. erectus pekinensis’s capabilities with respect to the use of fire. (1) Homo erectus pekinensis knew how to use fire and had the ability to control and maintain it. (2) They did not possess the capability to manufacture fire. Instead, they may have introduced naturally occurring fire into the cave. (3) They were not adept at maintaining fire throughout the period of their occupation of the site. Sometimes they had to live without fire, which is indicated by the lack of continuous accumulations of ash and charcoal. (4) The use of fire was very important for their survival. They used fire to keep dangerous predators out of their cave home, to cook food, to illuminate the dark niches of the cave, and to keep warm during North China’s cold winters. (5) The discovery and recognition of evidence of fire use at ZKD is a milestone in the history of research on human evolution (Zhang 2004).

The conclusion that in situ burning as a result of human activity occurred at the ZKD site was reinforced by later investigations. More burned materials and other pyrogenic traces were unearthed, and more physical and chemical analyses were conducted. In the 1980s, fission-track and thermoluminescence dating were carried out on sediment samples from the site, yielding reasonable ages for key cultural horizons that are roughly consistent with the ages obtained by other dating methods. This indicates that the sphenes in the Layer 4 and Layer 10 ash samples were heated above the annealing temperature during H. erectus pekinensis’s occupation of the site. Otherwise, ages obtained from these samples should be much older (Guo et al. 1980, 1991; Liu et al. 1985; Pei 1985). Therefore, these analytical results signaled high-temperature burning events at the site, especially from the Layer 10 ash remains.

In 2004, Shen et al. (2004) performed research on the presence of elemental carbon (EC) in various samples collected from ZKD Locality 1. “Elemental carbon” is an abbreviated
name for a C-rich, O-H-S-N-depleted substance produced in the process of combustion, and it usually occurs in charcoal, soot, fusain, microcrystalline graphite, carbon black, and similar substances and is considered one of the indicators of in situ use of fire by humans. Analyzed samples were taken from Layers 4, 7, and 10 and from natural, nonanthropogenic deposits outside the cave as well as from an ash lump collected in the 1930s curated in the ZKD site museum. Shen et al. (2004) discovered that the concentration of EC in the samples taken from Layer 10 is much higher than that from other samples and concluded that the sampling loci might have been close to a hearth.

Based on original field notes, excavation reports, and research papers, it can be concluded that the excavated materials and traces relating to fire-use activities in certain horizons at the ZKD site are abundant, comprehensive, and mutually supportive. While evidence for the in situ use of fire at ZKD was being questioned by some scholars, other researchers voiced strong support for this evidence. They argued that evidence of “controlled use of fire” at the site as a whole is clear, strong, and internally consistent and that any questions based on either limited taphonomic observations or analyses of samples taken from a few localized spots would not be sufficient (Liu et al. 1998; Zhong et al. 2014). Some also agreed that further research would be necessary to solve the issue and put an end to the controversy.

Historical Debates over the Evidence for Fire Use at Zhoukoudian

Ideas about Homo erectus pekinensis’s capability to use fire took a sudden turn in 1985 when Binford and Ho published their paper on the taphonomy at ZKD. From a taphonomic point of view, based on information derived from early field notes, photos, reports, and papers, they questioned the long-established notion that ZKD Locality 1 was the cave home of H. erectus pekinensis, the location to which hominins brought back game to share with the group and where fire was used and maintained to cook food and provide light and heat within the cave. First, they asserted that the association of hominin fossils and stone tools was weak and that the so-called ash layers were not hearth remnants and that no structured hearth arrangements could be confirmed. Second, they concluded that many, if not most, of the animal bones in ZKD Locality 1 were accumulated by hyenas, wolves, and other carnivores who occupied the site rather than by hominins as the consequence of hominin hunting behavior. They also suggested that the apparent ash was largely owl or other raptor droppings or the by-product of natural, nonanthropogenic fires. In the end, their conclusions were rather inconclusive: “What, then, was life like in the ‘cave home of Beijing man?’ We think we must conclude that we do not know. Hominids were regularly in the cave. They regularly used stone tools there and probably used fire there” (Binford and Ho 1985:429). Nevertheless, their statement was subsequently used as a starting point for a series of challenges to the notion that ZKD Locality 1 preserves evidence of human use and maintenance of fire.

In the following year, Binford and Stone (1986) published another paper on ZKD. This article was the outcome of Binford’s experiences during a short visit to the site and 4 days of examination of 1,523 pieces of animal bone from the cave. Binford identified carnivore chew marks, stone-tool cut marks, manganese stains, traces of fire alteration, and discrepancies in the taxa and skeletal elements represented. They concluded that the dominant contributors to the ZKD bone accumulations were denning animals, especially hyenas, implying that the hominins who occupied the cave were not big-game hunters but occasional scavengers. There was strong evidence for the controlled use of fire by H. erectus pekinensis during the late phases of occupation at the site, indicated by a small number of equid bones in the upper levels bearing evidence of burning. However, they maintained that such evidence for the early occupations was lacking because most of the blackened bones were actually mineral stained, and the few burned dry bones from the earlier levels were likely the result of modification by natural fires and were, therefore, not related to the behavior of hominins. The multicolored layers identified as ash yielded no evidence that these strata were produced by fire, and they believed that until they were subjected to more sophisticated analysis, their identification as ash would remain in question (Binford and Stone 1986).

The opportunity for such geochemical analyses finally arrived in 1996 and 1997 when Weiner et al. (1998) launched a systematic field project at ZKD that included section cleaning, sampling, and geological observations on the Western Section of Locality 1 along with subsequent geological, chemical, and taphonomic analyses and experimental studies. Their principal interest was looking for evidence of in situ use of fire. During the cleaning of geological sections, they collected 42 large-animal and 278 microfaunal elements mainly from the upper part of Layer 10 (Weiner et al. 1998). Five of the macrofaunal bone fragments were uniformly black to gray in color in fresh fracture surfaces. Infrared spectra showed that the insoluble residues extracted from the blackened bones were all characteristic of burned bone organic matrix. Seven microfaunal bones were uniformly black and probably burned. Many of the microscopic pieces of bone were well rounded, possibly due to transport or to carnivore digestion. In the “ash layer” in the upper part of Layer 10, they did not detect siliceous aggregates or sufficient amounts of potassium and other properties such as phytoliths as indicators of the presence of ash resulting from burning wood. As to the “hearths” reported in the lower part of Layer 10, they found that the deposits were in fact composed of finely laminated silt, clay, and organic matter, and they pointed out that the fine lamination of such sediment was created by still-water deposits.

In addition, this research team found several stone artifacts in the upper part of Layer 10 and observed a close association between those artifacts and the burned bones. They also no-
ticed that the percentage of the faunal assemblages that were burned (2.5% of the microfaunal remains and 12% of the large-animal bones) was similar to those observed in younger cave sites with clear evidence of the use of fire. Nevertheless, they noted that “as some of the sediments of Layer 10 were deposited under water, we cannot be sure that the bones, including the large burned and unburned bones, as well as the artifacts are in their original discard location” (Weiner et al. 1998:253) and concluded that

on the basis of the absence of ash or ash remnants (siliceous aggregates) and of in situ hearth features that there is no direct evidence for in situ burning in Layers 4 and 10. Most of the fine-grained sediments in the site were water laid, and even if ash remains could be recognized, it would be difficult to demonstrate where they were produced. The co-occurrence of burned black bones and quartzite artifacts in the same layers is only suggestive of a cultural association, and hence of the use of fire by humans, but does not prove it.

This research not only “damps ancient Chinese fires” but also called into question whether *Homo erectus* was capable of using fire (Wuethrich 1998).

In 2000, Boaz and his colleagues published a paper in which they concluded that hyenas were responsible for most of the faunal accumulation and modification at the site, including that of *H. erectus*, and that hominins did not occupy ZKD Locality 1. Instead, their remains were transported into the cave by hyenas. They suggested that further research was needed to determine the true nature and scope of the presence of stone tools, cut marks on bone, and fire in the cave (Boaz et al. 2000).

In 2001, Goldberg and his colleagues published a detailed geological analysis of ZKD as another important outcome of the 1996–1997 field project. They stated that sediments from Layers 10 through 3 show extensive water deposition of fine, silt-sized material derived from outside the cave. They suggested that the site was open to varying extents throughout most of its depositional history and that the so-called ashes in Layer 4 represent subaerial water-laid silt deposits accumulated after the collapse of the brecciated roof during the formation of Layer 6 (Goldberg et al. 2001). They concluded that no irrefutable evidence of in situ burning by humans in any horizon of the deposits at ZKD could be found. In 2004, Boaz et al. (2004) reinforced their interpretation of *H. erectus pekinensis*’s pyrotechnological skills. Based on their analysis of published and unpublished sources, they constructed a digitized three-dimensional excavation grid of Locality 1 to assess the spatial relationships of the human fossils, artifacts, and other materials. Their observations are largely a reiteration of the research results reported by Goldberg et al. (2001), but Boaz et al. (2004:546) nevertheless concluded that “despite recent geochemical and sedimentological studies that modify earlier interpretations of the use of fire at the site, there are signs that fire was used by hominids at Zhoukoudian.”

Recent Investigations and Research Results

Systematic research-oriented salvage excavations have been undertaken at the Western Section of ZKD Locality 1 since 2009. These new excavations are aimed at rescuing fossils, artifacts, and taphonomic information from blocks of sediments in imminent danger of erosion and collapse, stabilizing extant deposits and profiles, searching for new archaeological remains using up-to-date field technologies, and conducting systematic geological sampling and multidisciplinary analyses to reconstruct the formation history of the site and to resolve various controversies, including the issue of hominin use of fire. The excavation area was initially about 20 m² and is now less than 10 m² in because of the slope of the South and West Sections and the sharp incline of the original cave wall to the north. Thus far, the excavation has cut through Layers 3, 4, and 5 and has reached the upper part of Layer 6, during which nearly 5,000 stone artifacts (mainly flakes, cores, chunks, and scrapers made on vein quartz) were unearthed along with numerous vertebrate fossils (Zhang et al. 2016). Most of the excavated materials derive from Layer 4, the Upper Cultural Horizon, which clearly indicates that the formation of this unit is closely associated with hominin activities. Considerable progress has been made on the analysis of the lithic collection and verification of fire use as a result of these new field investigations.

New Discoveries and Observations in the Field

Discoveries relevant to evidence of the use of fire by *Homo erectus pekinensis* recently derived from Layer 4 include the following data classes and phenomena:

a) *Burned areas or hearths*. Three areas characterized by intense rubification of sediments and concentrations of potential ash remnants were encountered. Two loci yielded signals of high magnetic susceptibility, rubification, and maximum heating temperatures (more information on such analyses is given below) and thus can be identified as hearths. One such feature is outlined by rocks (fig. 3a).

b) *Burned bones*. Many uniformly black mammalian bone fragments were recovered from this horizon, providing clear information on provenience, taphonomy, and association with lithic artifacts (fig. 3b).

c) *Heated limestone and lime*. A pile of limestone blocks in the northeastern corner of the excavation pit was determined to have been severely heated, and some pieces were already transformed into white lime. These rocks may have been part of a constructed hearth; however, their enclosing matrix had already collapsed, thus no clear structure remained.

d) *Evidence of a cave or rock-shelter*. A large pile of limestone breccia of various sizes was encountered on top of Layer 4 sediments in the northern part of the excavation pit. This is clearly the result of the collapse of the cave roof, indicating that during the formation of Layer 4, at least part of
ZKD Locality 1 retained the integrity of a cave suitable for hominin occupation, and the collapse process at other parts of the cave could have started earlier.

e) The role of water in the deposition of sediments. Bedding structures were detected in certain layers and loci in this horizon, but it is not a uniform phenomenon. Such deposits occurred mostly in the southwestern corner of the excavation area. Excavation clearly demonstrates that the Layer 4 deposits dip toward the southwest. Therefore, that part of the cave must be lower than other locations and thus more easily subject to the action of water.

f) The Layer 4 deposit at ZKD Locality 1 is thick and complicated. This unit can be further divided into several discrete strata representing different taphonomic processes including geological and anthropogenic agents. While some strata could be the result of primarily natural processes, some may be closely related to the activities of human ancestors.

The Extraction of Siliceous Aggregates and Experimental Studies

The absence of siliceous aggregates and potassium in Layer 10 is the principal reason that Weiner et al. (1998) argued that there was no clear evidence for in situ fire use at ZKD. New attempts have been recently made to extract siliceous aggregates and other botanical microfossils from the upper part of the deposits at ZKD Locality 1 (Zhong et al. 2014). Four samples were extracted from potential ash accumulations in Layer 4 and Layer 6 (three from the former and one from the latter), where new excavations exposed fresh deposits more suitable
for such analysis. The samples were soaked in 6N hydrochloric acid (HCl) and 6N nitric acid (HNO₃), respectively, for 24 hours. After drying, a Hitachi S4800 field-emission scanning electron microscope was used to analyze the elemental composition of the insoluble phases in these samples, and a Bruker D8 advance X-ray diffractometer was employed to analyze their material composition.

The results revealed a large number of sintered agglomerates present in the insoluble residual phases of the samples, and the elements associated with siliceous aggregates (Al, Si, Fe) were evident in all samples (table 1). In all four samples, silicon content was highest, followed by aluminum. Potassium, which can only be preserved in siliceous aggregates, and iron were detected in lower concentrations. Material composition analysis demonstrated that the substances in the potential ash remnants existed mainly in the form of SiO₂, EC, elemental potassium, and silicates. The test results show clearly the presence of EC, elemental K, and siliceous aggregates in the insoluble phases of the ash from Layer 4 and Layer 6 and that "these results should spur reconsideration of the conclusions drawn by Weiner and his colleagues and provide additional supporting evidence of in situ controlled use of fire by Homo erectus pekinensis at Zhoukoudian Locality 1" (Zhong et al. 2014:341).

Burning experiments were conducted at the site using wood sourced from 12 arboreal species including hackberry (Celtis sp.) and Chinese redbud (Cercis chinensis). These species were found to have been in the environment of H. erectus pekinensis, either recovered as burned fragments or identified through pollen analysis on sediments extracted from the site. Through elemental composition and material analysis of the fresh ash, the presence of silicate aggregates was determined and, more importantly, an enormous discrepancy was discovered in the levels of constituent chemical elements (Si, Al, Fe, and K) contained in fresh ash resulting from burning the wood of different trees (table 1). From this, we may reasonably conclude that the samples analyzed by Weiner et al. (1998) happened to have derived from the burning of arboreal species containing low quantities of siliceous aggregates and elemental potassium. Therefore, samples taken from different loci in the section may produce highly variable results and lead to different conclusions.

### Research on Magnetic Susceptibility and Color Measurements

Another series of analyses carried out recently at ZKD Locality 1 involved detailed measurements of magnetic susceptibility, color, and diffuse reflectance spectra of sediments in the area newly exposed during recent excavations in Layer 4 (Zhang et al. 2014). Magnetic analysis and color measurements have been proven to be effective methods for detecting the presence of heated areas in archaeological sites (e.g., Carano and Villalain 2011; Jordanova, Petrovsky, and Kovacheva 2001). In order to analyze the sedimentary features of the excavation pits and determine the extent of the potentially burned areas, systematic sampling was employed in three zones identified as possible burned areas or “hearths” as well as apparently unburned areas in the same level. A total of 405 samples were collected. Magnetic susceptibility was measured with an Agico MFK1-FA Kappabridge magnetic susceptibility meter at frequencies of 976 Hz (vLF) and 15,616 Hz (vHF). Redness was measured with a Konica Minolta CM-700d spectrophotometer. Following magnetic susceptibility and redness measurements, some samples were then selected for DRS and high-temperature magnetic susceptibility measurements (fig. 4). The results indicate that the magnetic susceptibility and redness of sediments taken from the hypothe-
ical “hearth”s were markedly higher than those from other areas in the same level (up to 22 times greater for magnetic susceptibility and three times more for redness), and fine-grained magnetite and hematite grains contributed significantly to the distinctly high values of magnetic susceptibility and redness in these “hearth” sediments. High-temperature magnetic susceptibility measurements demonstrated that the thermally altered sediments were heated to above 700°C. Those changes in low-frequency magnetic susceptibility and redness cannot result from natural fires (Zhang et al. 2014).

Discussion

In the past, many Paleolithic sites, including ZKD, have been reported to have yielded evidence for the use and maintenance of fire by early hominins. However, many such localities, especially those of the Lower Pleistocene and even the early Middle Pleistocene, have been questioned because of the lack of solid supporting evidence (Sandgathe and Berna 2017). How can we effectively evaluate evidence of in situ anthropogenic burning, and what criteria should be used and accepted by researchers to achieve consensus on this matter? Certainly, the presence of fire-cracked rocks, burned bones and artifacts, ash, charred botanical materials, burned sediments or ground surfaces, and residues of combustion are important. However, in many cases it is intact fire features (fireplaces or “hearth”s), the context of these individual occurrences, and their association with other human remains (e.g., human fossils and artifacts) that are emphasized. Weiner et al. (2000:221) proposed the following criteria and degrees of confidence for evaluating in situ burning at archaeological sites (table 2).

In theory, the criteria proposed by these scholars are objective, clear cut, and feasible. However, in practice, they are often very difficult to apply to many Paleolithic cases because

<table>
<thead>
<tr>
<th>Objects and associations</th>
<th>Degree of confidence</th>
</tr>
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<tbody>
<tr>
<td>Constructed fireplaces and hearths (e.g., depression, stone lined) preferably in association with burned bones, lithics, sediments, etc.</td>
<td>Clear-cut evidence for intentional fire use by humans</td>
</tr>
<tr>
<td>Unambiguous associations, e.g., in situ presence of wood ash in a cave where trees are not normally found (i.e., interior portions)</td>
<td>Evidence for fire use by humans</td>
</tr>
<tr>
<td>Ambiguous associations, e.g., burned bones associated with lithics in a stratigraphic unit or layer</td>
<td>Suggestive evidence for fire use by humans</td>
</tr>
<tr>
<td>Presence of burned materials dispersed in a depositional context without direct association with anthropogenic products</td>
<td>Evidence for fire at site but not proof of direct or purposeful human use</td>
</tr>
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</table>

human and other animals’ activities during the formation of the archaeological record as well as geological factors of post-depositional processes could all alter the traces left by humans who made use of the site. Thus, ideal archaeological sites in which human behavioral evidence remains completely intact will be very difficult to find. In general, the older the archaeological deposit, the worse the evidence is preserved. However, we can still use the criteria proposed by Weiner et al. (2000) to evaluate the nature and authenticity of the evidence for the use and maintenance of fire from ZKD Locality 1, especially Layer 4.

The presence of burned materials dispersed throughout the deposit—including fire-cracked rocks, burned animal bones, and charred botanical remains—has been clearly documented at ZKD Locality 1, especially in Layers 4, 8–9, and 10. Therefore, while the site retains evidence of fire, no unambiguous proof of direct or purposeful human maintenance of fire has emerged. Although these items were found along with lithic artifacts and human fossils in the same stratigraphic units, these associations are regarded as ambiguous by some researchers. Thus, only suggestive evidence for the use and maintenance of fire by early hominids at the site has been preserved. The recent field investigations in Layer 4 revealed that anthropogenic fireplaces and hearth features illustrated by stone-outlined features, siliceous aggregates, and extremely high redness values and magnetic susceptibility in association with burned bones, stone artifacts, and latosols are clearly present in the deposits, thus providing clear-cut evidence for intentional fire use by hominins at the site, at least during the formation of that horizon.

But what of the other Locality 1 horizons, especially Layer 8–9 and Layer 10, so long claimed to be rich in burned materials and other pyrogenic traces, even hearth remnants? Goldberg et al. (2001) paid particular attention to Layer 10 during their field investigations. They argued that there was no clear evidence of anthropogenic fire use in the Lower Unit of Layer 10 and concluded that a major part of this unit is the product of deposition in standing or slowly flowing water. With respect to the Upper Unit of Layer 10, they expressed uncertainty. They pointed out that the Upper Unit deposits contained both quartzite pebbles presumed to have been brought to the site by humans and allochthonous rock fragments that appear to have a fluviatile origin; therefore, the possibility of human activity could not be ruled out (Goldberg et al. 2001).

It is clear from these scholars’ description that Layer 10 is thick and has a long and very complicated depositional history and that the site might have been open to varying extents throughout most of the period of its formation. Therefore, many agencies, both human and natural, may have contributed to the accumulation of sediments in this horizon. Shen et al.’s (2004) analysis of the distribution of EC identified much higher concentrations in Layer 10, strongly suggesting that fireplaces had existed here during this earlier period. Another piece of evidence in support of this conclusion is the observation that the lower horizon of Layer 10 may be correlated with the Quartz II layer in the Gezitang (Chamber or Hall of the Pigeons), where two concentrations of ash were found deposited conformably on top of a large limestone slab (Pei and Zhang 1985). It is possible that hearth features, or at least some subset of them, were disturbed or even destroyed by natural postdepositional processes such as hyena denning and water movement. Early excavators at ZKD may have encountered undisturbed features of this type in other parts of the horizon, leading them to report the existence of evidence for hominin use and maintenance of fire in this stratum. We can only hope that future excavators at ZKD will be fortunate enough to find such clear-cut evidence testifying to the early development of nascent pyrotechnologies at the site.

According to the field notes and research reports of earlier ZKD excavation projects, Layer 8–9, the so-called Lower Cultural Horizon, yielded much more evidence of human fire use than did Layer 10, including several layers of ash and burned objects (Jia 1959; Pei and Zhang 1985). However, little recent effort has been made to investigate this important horizon. Even in the investigations by Goldberg et al. (2001), little attention was paid to these strata. They provided a relatively simple description of Layer 8–9: “The broken, dislodged and rotated nature of the aggregates and the interstitial infillings of well sorted silt, suggest disturbance of the original deposits by water, including inwashing of silt” (Goldberg et al. 2001: 497–498). Considering the fact that abundant archaeological materials and traces related to human use of fire have been documented in Layer 8–9 and that three Homo erectus crania were unearthed from this unit in 1937 (Jia and Huang 1990), the Lower Cultural Horizon deserves much more research attention because future excavation and analysis might produce more convincing evidence of in situ use and maintenance of fire by early hominids similar to that obtained from Layer 4.

The debate over hominin use and maintenance of fire at ZKD provides an interesting basis for examining the ways in which the scientific community has dealt with key academic issues and changes through time: some might relate to the application of new technologies to extract new evidence, and some might be subjective assertions inspired by theoretical paradigm shifts. Binford and Ho’s (1985) claims (that burned items evident in ZKD Locality 1 were probably brought into the cave by flowing water, that the so-called ash deposits were actually made up of bat or bird dung or simply chemical-altered humus or the residues of nonanthropogenic wildfires, and that ZKD could not be considered the real “cave home” of Peking Man but was instead the lair of denning carnivores) were not based on any primary research at the site or on excavated materials. They did briefly visit the site later and analyzed collections of bone (Binford and Stone 1986), but a half-day observation of the profile and 4 days of examination of 1,523 pieces of animal bone could hardly produce precise and unbiased data (see comments by Behrensmeyer, Haynes, and Olsen in Binford and Stone 1986). Their argument was essentially a consequence of the shift in ideas about the ca-
pabilities and inclinations of early hominins to acquire meat, that is, from perceptions emphasizing systematic hunting to situational scavenging. This factor is very obvious in their willingness to accept evidence of fire use from Layer 4 but refute it from Layer 10. They took this stance not because they detected significant differences in the burned materials from these two horizons but only because Layer 4 was deposited much later, thus the inferred capability of hominins to hunt large game and use fire for that younger stage was more acceptable. In doing so, earlier, potentially equally compelling, evidence was either denied or simply neglected.

Binford’s verdict on the nature of the ZKD site and the fate of its evidence of hominin fire use had a profound effect on other researchers who seemed to be following the same path. This includes Boaz et al. (2000), who suggested that *Homo erectus pekinensis* did not occupy Locality 1 but that their remains were transported into the cave by hyenas, and they subsequently proposed “a model of transient hominid scavenging aided by the use of fire at the large hyenid den” (Boaz et al. 2004:519–520). It also includes Weiner et al. (1998) noticing a close association among stone artifacts and burned bones from Layers 10 and 4 and burned bone patterns similar to those observed in caves with unequivocal evidence of fire use by later humans but still claiming that it was “only suggestive of a cultural association, and hence of the use of fire by humans, but does not prove it” (Weiner et al. 1998:253).

These data can certainly be interpreted in other ways. For example, Wu Xinzhi (1999) used the burned bone values obtained by Weiner et al. (2.5% of the microfaunal and 12% of the macrofaunal assemblages were burned) to refute their conclusion that those bones were transported into the cave by water runoff, arguing that water transport would have yielded much smaller proportions of macrofaunal bones compared with microfaunal elements and that stone artifacts would not have been easily moved under such conditions.

One especially interesting observation was made by Goldberg et al. (2001). They suggested that the Upper Unit of Layer 10 could be partially related to human activity because of the presence of stone tools and blackened bones, and they believed that human occupation of the cave would not have been contemporaneous with hyenas. This conclusion provided a kind of inspiration in addressing the question of whether ZKD was, in fact, the “cave home” of *H. erectus pekinensis* or the den of hyenas or cave bears because both early hominids and large carnivores made use of the cave during certain periods throughout the long history of its formation and evolution. What we describe here is a long and complex occupational story; the appearance on the scene of one character should not exclude others; they were all protagonists on the stage during different acts.

**Conclusions**

The evidence for *Homo erectus pekinensis* use and maintenance of fire at ZKD Locality 1 had been accepted as a matter of course for more than half a century until it began to be seriously questioned in the mid-1980s. While some of the questions have been based on new research results, some are at least partially hypothetical and speculative. In the latter case, previous evidence and analytical results have been largely ignored. Geochemical investigations conducted at the site in the 1990s provided new perspectives and deepened studies of this issue. However, the results have certain weaknesses due, in part, to limitations in sample collection and the resulting data. The field investigations and laboratory analyses, ongoing since 2009, have unveiled new and reliable evidence supporting the use and maintenance of fire by hominids at ZKD. Current evidence suggests that Layer 4 of the site contains clear-cut evidence for in situ use of fire, including hearth features. Future excavations and research conducted at Layers 8–9 and 10 may reveal similar evidence to definitively resolve this continuing controversy.

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How Did Hominins Adapt to Ice Age Europe without Fire?

by Harold L. Dibble, Aylar Abodolahzadeh, Vera Aldeias, Paul Goldberg, Shannon P. McPherron, and Dennis M. Sandgathe

Throughout history, pyrotechnology, a uniquely human technological innovation, has been seen as a major factor in allowing humans to adapt to a wide range of environmental circumstances. But as noted recently by Shimelmitz et al. (2014:196), “only when fire use became a regular part of human behavioral adaptations could its benefits be fully realized and its evolutionary consequences fully expressed.” Recently a series of papers was published (Aldeias et al. 2012; Goldberg et al. 2012; Sandgathe et al. 2011a, 2011b) looking at the evidence for combustion features at two sites in southwest France, Roc de Marsal and Pech de l’Azé IV. At both sites two patterns were apparent. First, there were long periods of time when, in spite of extensive evidence for ongoing occupation, evidence for the use or presence of fire was lacking. Second, as indicated by the dates and faunal remains, these periods of little or no use of fire reflected a time of increasingly cold conditions. Given an abundance of evidence for fire use earlier in the sequences of both sites during the warmer periods of MIS 5, the lack of evidence during the colder periods was especially surprising. Earlier, we suggested (Sandgathe et al. 2011a) that these European hominins lacked the ability to start fires, relying instead on natural fires. This suggestion was based on the fact that most wildfires are caused by lightning strikes and that lightning occurs much more frequently during warmer and wetter periods and more rarely during cold, dry periods. Regardless of the reason for the long hiatus, however, if fire were not being used during long periods of occupation at these sites, this raises important questions regarding the role of fire in the overall evolution of human behavior.
adaptation of these hominins to the colder conditions of MIS 4 and MIS 3. Some of these questions will be addressed later in this paper. First, however, it is important to review the evidence from these two sites and others that have been studied subsequently, taking into account some results of recent laboratory experiments on the transfer of heat from surface fires to underlying sediments (Aldeias 2017; Aldeias et al. 2016).

Evidence for Presence and Absence of Fire at Pech de l’Azé IV and Roc de Marsal

Pech de l’Azé IV (Pech IV) and Roc de Marsal are two Mousterian cave sites in the Dordogne region of southwest France (fig. A1; figs. A1–A7 available online) recently excavated by the same multidisciplinary team from 2000 to 2010 (Dibble et al. 2009; McPherron, Soressi, and Dibble 2001; Sandgathe et al. 2008; Türg et al. 2009, 2011). Both sites span the period of time from mid to late MIS 5 into MIS 3. At both sites there is clear evidence for fire use in the basal layers and very limited evidence of it in the upper layers.

Pech IV contains several major geological strata of Pleistocene-age sediments (fig. A2). The lowermost, Layer 8, lies directly on bedrock (see Dibble et al. 2009) and is dated by thermoluminescence (TL) and optically stimulated luminescence (OSL) to approximately 95 ± 5 kya, or MIS 5c (Gibbard and van Kolfschoten 2005; Jacobs et al. 2016; Richter et al. 2012; Winograd et al. 1997). In keeping with these dates, the associated fauna also suggests a warm, humid climatic regime (Dibble et al. 2009; Laquay 1981; Niven 2013). Evidence for fire, including clear organic- and ash-rich units, burned bone, burned lithics, and rubefied (reddened) sediments is abundant in this layer.

In the overlying layers, there is little direct evidence of fire. Following the heavily disturbed Layer 7, Layer 6 is also associated with a faunal assemblage (fig. A3) that reflects a relatively temperate wooded environment and dates to approximately 77 kya (Jacobs et al. 2016). Although in his earlier excavation of the site, Bordes (1975) did observe some limited traces of fire residues in this layer, our own excavations did not. Following another partially disturbed layer (5B), Layer 5A represents the beginning of a colder period, with a significant increase in reindeer, and this trend to colder conditions continues through Layer 4, which dates to around the beginning of MIS 4. The final Pleistocene layer, Layer 3, is dated by a number of methods (see also McPherron et al. 2012) to around 50 kya, or MIS 3. Virtually no direct evidence of fire was seen in Layers 4 and 5, although burned bones were observed in thin section and some dispersed charcoal occurred in Layer 3.

Another Middle Paleolithic site excavated by the same team is Roc de Marsal, which is located about 20 km west of Pech IV (Türg et al. 2009). Here excavations recognized 13 stratigraphic layers (fig. A4). At the base, Layers 13 through 10 represent locally mobilized sediments from weathering of the limestone bedrock. Layer 10 contains some limited archaeological materials (n = 129 lithics), but these may be mostly or entirely intrusive. Artifact densities in Layers 9 through 2 are very high (e.g., n = 8,100 lithics for Layer 9). Layer 1 is a disturbed Holocene deposit.

Layers 9 through 5 comprise a single lithostratigraphic unit with significant interbedded darker anthropogenic components including major concentrations of ash, charcoal, and burned objects. The faunal data (fig. A5) indicate temperate conditions with an abundance of forest species, suggesting a late MIS 5a date (Marquet in Sandgathe et al. 2008). The overlying layers, Layers 4 through 2, show increasingly colder and drier conditions that would correspond to MIS 3 (see Castel et al. 2016; Guérin et al. 2012, 2016; Sandgathe et al. 2008).

As at Pech IV, direct evidence for fire (see Aldeias 2017) is found not throughout the Roc de Marsal sequence but rather only in the earliest layers. This evidence includes discrete charcoal and ash units, burned or calcined bone, burned lithics, and rubefied sediments (Aldeias et al. 2012; Goldberg et al. 2012). In Layers 7 and 9 localized examples of “stacked” hearths are clearly visible in section view (fig. A6), which indicates that individual hearths were repeatedly constructed in more or less the same location throughout the duration of each of these stratigraphic components. However, not all of the lower layers exhibit direct and intensive evidence for fire and in fact, such evidence alternates: Layers 5, 7, and 9 are rich in such features, while Layers 6 and 8 have little or no direct evidence for them. Abundant hearths in the lower levels of the site were also mentioned in the unpublished notes of the previous excavator, J. Lafille.

To summarize (and as shown in fig. A7), the Middle Paleolithic occupations of Pech de l’Azé IV and Roc de Marsal overlap considerably in time, with initial occupations during a temperate period followed by occupations that occurred during a marked deterioration in climate. At both sites unmistakable hearth features occur in their lower layers and indicate that fire was certainly used at this time, that is, during the time of relatively warmer conditions. But it is equally clear from both sites that fire use was not a constant element in the occupations. At Roc de Marsal, for example, the lower layers seem to alternate between those with clear fire residues and those without. At both sites, however, the upper Mousterian layers (Layers 4 through 2 at Roc de Marsal and Layers 5 and 4 at Pech IV) contain no identifiable fire features, including no concentrations of charcoal or ash and limited quantities of burned bone or flint. At best, very rare and very small fragments (<0.5 cm) of charcoal were noted, and these were primarily confined to Layer 3 of Pech IV (where there are also slightly more heated flints).

How Good Are These Data?

The primary question to be addressed first is whether or not the absence of direct evidence for fire is indeed evidence of fire’s absence. With regard to taphonomic factors, strong arguments can be made to show that postdepositional processes were not significant factors in removing the direct evidence.
First of all, at both sites well-preserved fire residues occur both inside the caves as well as beyond what would have been the drip lines at the time of occupation. Therefore the degree of overhead cover is not a factor. Furthermore, there is no evidence in the form of edge damage on the lithic artifacts, preferred orientations of objects, winnowing of smaller objects, or micromorphological studies of the sediments to indicate significant post-depositional disturbances or erosion in the upper layers of either site. Thus, no site formation processes have been identified that could have removed the fire residues.

Nonetheless, even if direct evidence for fire may be have been removed, there should be indirect evidence due to the effects that heat has on lithics, bones, and even the sediment, and all of these should remain (Aldeias 2017). When flint is exposed to heat, color changes can be visible at temperatures starting at 250°C, a distinctive luster begins to develop at temperatures of approximately 350°C, and crazing can occur starting at 320°C (Julig et al. 1999:838 and citations within; Rottländer 1983). These effects are not limited to objects that are actually in the fire. A series of actualistic experiments (Sievers and Wadley 2008; Stiner et al. 1995; Werts and Jahren 2007), as well as more highly controlled ones (Aldeias 2017; Aldeias et al. 2016), has suggested that the heat from fires can transfer to underlying sediments, though exactly how far down and the rate of transfer are dependent on several variables. For example, figure 1 below shows the results of two heat experiments at two different temperatures (950°C and 600°C) at the ground surface, with additional temperature readings at depths of 2, 6, 10, and 20 cm. Even at the cooler surface temperature of 600°C, objects 2 cm below the surface will heat to 300°C within an hour, and at higher temperatures and with longer duration, temperatures as high as 200°C will be reached at even 10 cm below the surface. Thus, even relatively small and/or brief fires will affect underlying objects.

Instead of simply noting the presence of burned flints in the two sequences, the number of proximal and complete pieces showing signs of burning is expressed as a percentage of all proximal and complete pieces (in both cases counts are for pieces larger than 2.5 cm; see fig. 2). At both sites the percentage of burned lithics and fauna decreases through the sequence, reaching minima of 1%-2% in the upper layers. As shown in Sandgathe et al. (2011a), the numbers are a function of neither varying sample size nor artifact density. Even if the direct evidence for the combustion features were removed, it is highly unlikely that the same processes would remove the objects that were either in direct association with the fire or embedded in sediments directly below the fire.

At both sites, then, the percentage of burned lithic objects, which is not subject to preservation issues, generally agrees with the direct evidence of fire residues in that the use of fire

Figure 1. Results of controlled experiments on heat transfer from ground surface down into the substrate (in this case sand). The experiment was run with the surface heat source set at 950°C and again at 600°C. Temperatures were continually recorded at the ground surface and at 2, 6, 10, and 20 cm beneath the heat source (see Aldeias et al. 2016).
far more likely explanation is that heat from fires was not expected if substantial mixing had occurred. The pattern in the basal layers of Roc de Marsal provides an earlier example of some of the lithics of Layers 6 and 8, and in particular at the sites of Pech de l’Azé IV and Roc de Marsal, while understanding the duration and intensity of individual occupation events is difficult at best, it is clear that these were both consistently used as occupation sites. The significant concentrations of stone tools (made and used in all components of both sites) and heavily butchered faunal remains throughout the entire sequences (Castel et al. 2016; Hodgkins et al. 2016; Niven 2013) are evidence of this. It would be very difficult to argue that at times, the sites served more ephemeral purposes (e.g., that they were kill sites or secondary butchery sites) where the use of fire may have been less likely. In addition, the alternating pattern in the basal layers of Roc de Marsal—where fires present in Layers 5, 7, and 9 and absent in Layers 6 and 8—provides another argument against fires being associated with only certain kinds of site use (see figs. 3, 4). Both the burned and unburned layers show virtually identical technological and typological characteristics.

Although faunal data are incomplete for Roc de Marsal, it is clear that while the prey species varies throughout both site sequences, the kinds of anatomical elements represented are virtually indistinguishable in layers with fire versus those without. Most frequently, the elevated percentage of heated flints remains high even though there are no visible hearths in these layers. Although it might be suggested that the elevated percentage of heated flints might represent some vertical movement of lithics, there is currently no micromorphological or field evidence for this. Likewise, generally there are some clear time-related patterns in these layers (9–5) that are not expected if substantial mixing had occurred. The far more likely explanation is that heat from fires in overlying layers moved down through the sediments (i.e., the fires in Layers 5 and 7 modified some of the lithics of Layers 6 and 8, respectively; see Aldeias 2017; Aldeias et al. 2016).

It is also unlikely that during the later occupations fires were constructed at other lateral and as yet unexcavated locations at the sites. At Roc de Marsal, the majority of the site has now been excavated (when combining our own excavations with the previous excavations of Lafille). The morphology of the cave in relation to the remaining sediments makes it very unlikely that evidence of fire remains to be detected there by some future excavation. Our own excavations extended along the entire length of deposits from well in front of the drip line to the rear of the cave, as well as laterally across the width of the cave. If there had been any other fire residues (including burned flints), they would have been detected. This issue is a bit more problematic at Pech de l’Azé IV because our own excavations were concentrated on the western section of the excavated area, that is, the side that is closest to the original (and now collapsed) entrance of the cave (Turq et al. 2011). However, observation of the eastern section remaining from Bordes’s (1975) earlier excavation clearly indicates the same level of burning in the basal deposits and a similar lack of such traces in the upper layers. Furthermore, analysis of Bordes’s entire collection, which represents a much larger area than our own, shows an identical pattern of decreasing percentages of burned lithics through the sequence (see fig. 2). Moreover, these two excavations were concentrated directly in the middle of the major part of the deposits, as determined by topographic relief.

In summary, both Pech IV and Roc de Marsal have excellent preservation, and the correlation is high between the presence or absence of direct evidence for fire (i.e., ash, charcoal or burned bone, rubefied sediments) and the indirect evidence of burned artifacts (see Aldeias 2017). This relationship is not surprising given the causal nature of one to the other, but it means that the presence of fire can be detected even though various taphonomic processes may have obliterated the more direct evidence. Therefore, in the absence of both direct and indirect evidence, the conclusion that fire was not present at particular times during the occupation of these two sites is much stronger than it would be by relying on the direct evidence alone. It would seem unavoidable to conclude, therefore, that, while fire was being used frequently and/or intensely during the earlier occupations, its use drops to near zero in the upper occupations. While evidence for the use of fire does not disappear entirely, on the basis of the very low frequency of burned flints, this evidence represents an insignificant aspect of these later occupations.

How Can We Explain These Patterns?

What has been shown is that at these two sites fire was absent over significant periods of time, potentially over thousands of years of repeated occupation and use of the sites. Is it possible to argue that how these sites were used changed over time? The answer to this question would appear to be no. For both Pech de l’Azé IV and Roc de Marsal, while understanding the duration and intensity of individual occupation events is difficult at best, it is clear that these were both consistently used as occupation sites. The significant concentrations of stone tools (made and used in all components of both sites) and heavily butchered faunal remains throughout the entire sequences (Castel et al. 2016; Hodgkins et al. 2016; Niven 2013) are evidence of this. It would be very difficult to argue that at times, the sites served more ephemeral purposes (e.g., that they were kill sites or secondary butchery sites) where the use of fire may have been less likely. In addition, the alternating pattern in the basal layers of Roc de Marsal—where fires present in Layers 5, 7, and 9 and absent in Layers 6 and 8—provides another argument against fires being associated with only certain kinds of site use (see figs. 3, 4). Both the burned and unburned layers show virtually identical technological and typological characteristics.

Although faunal data are incomplete for Roc de Marsal, it is clear that while the prey species varies throughout both site sequences, the kinds of anatomical elements represented are virtually indistinguishable in layers with fire versus those without.
without (see fig. 5; Castel et al. 2016; Hodgkins et al. 2016; Dibble et al. 2017, pt. 3). Again, this suggests that the presence or absence of fire does not appear to reflect changes in site use. Likewise, while there is no evidence either for or against the use of fire for cooking, the arguments of Wrangham (2009) concerning the benefits that could be derived from cooking suggest that if fire were available, it would tend to be used for this purpose under all circumstances. In other words, it would be difficult to argue that these Neanderthals simply changed their tastes in food preparation for millennia.

Since one of the primary uses of fire ethnographically is for warmth, it is especially ironic that in these two sites the use of fire drops off significantly during colder periods. This pattern is repeated at several sites in the region where we have comparable data. At Combe-Capelle Bas, which was excavated and analyzed using identical techniques, there was also no direct

![Figure 3. Percent frequencies of technological types in burned layers (layers with significant evidence for use of fire) compared to unburned layers (layers with little or no evidence for use of fire) at both Pech de l’Azé IV and Roc de Marsal.](image3)

![Figure 4. Percent frequencies of major tool types in burned layers (layers with significant evidence for use of fire) compared to unburned layers (layers with little or no evidence for use of fire) at both Pech de l’Azé IV and Roc de Marsal.](image4)
evidence of fire residues, and the percentage of burned flints remained at <2% for the entire sequence (Dibble and Lenoir 1995). This site, which contains Quina Mousterian assemblages, has been dated to MIS 3 (Valladas et al. 2003) and is thus contemporary with the nonfire occupations from Pech de l’Azé IV and Roc de Marsal. Similarly, the Quina layers at Jonzac and La Quina (Bierwirth 1996; McPherron et al. 2006; Niven et al. 2012) are associated with very high percentages of reindeer, and the percentage of heated flints is less than 0.5%. At Jonzac, the Quina layers have been TL dated to MIS 4 (Richter et al. 2013). In the overlying layers at these two sites, heated flints are never more than 4% of the assemblage, and they generally are much less. A similar pattern is noted at La Ferrassie, which exhibits Levallois industries similar to those at Roc de Marsal, little evidence of fire, and again occupations occurring during cold periods (Guérin 2015).

One of the best sites in the region for testing a correlation of fire and climate is Combe Grenal, where some 64 layers likely represent deposits from late MIS 6 through MIS 3. Data from Bordes’s collection (the site is currently being reexcavated) also indicates a correlation between climatic regime and frequency of fire use. This is based on percentages of burned flints recorded for 23 of the 64 layers identified by Bordes (Bordes, Laville, and Paquereau 1966). As can be seen in table 1, there is a general tendency, with some exceptions, for frequencies of burned flints to increase in those layers that were identified, through associated fauna (see Chase 1986) and sedimentology (Guadelli and Laville 1988), as being associated with warmer and wetter climatic periods. These data provide some of the comparable quantitative data called for by Sorensen (2017) but contradict his conclusions for this important site based on the number of observations (e.g., presence of purported fires in particular layers, heated bedrock, burned bones taken for AMS dating, TL samples taken for dating, etc.). More work is needed to reconcile these differences, but it should be emphasized that comparable proxies on relative scales are preferable to presence or absence data and that techniques such as micromorphology and FTIR (Fourier transform infrared spectroscopy) are preferable for identifying fire features. This said, we also acknowledge that curation issues with the Combe Grenal collection may impact proxies based on counting heated flints (Dibble et al. 2009).

We cannot exclude the possibility that all of these nonfire occupations were limited to summer months and that what we are seeing at these sites is a switch in seasonality wherein southwest France was only occupied during warm months. It
Table 1. Climate and frequency of burned flints in sampled layers of the Middle Paleolithic site Combe Grenal in southwest France

<table>
<thead>
<tr>
<th>Layer</th>
<th>Climate</th>
<th>% lithics burned</th>
<th>N lithics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–4</td>
<td>Very cold, very dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>5</td>
<td>Very cold, very dry</td>
<td>0.0</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Very cold, very dry</td>
<td>0.0</td>
<td>170</td>
</tr>
<tr>
<td>7–8</td>
<td>Less cold, humid</td>
<td>0.0</td>
<td>430</td>
</tr>
<tr>
<td>9</td>
<td>Cold and dry</td>
<td>1.9</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
<td>Cold and dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>11–13</td>
<td>Less cold, humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>14</td>
<td>Very cold, very dry</td>
<td>1.9</td>
<td>1,227</td>
</tr>
<tr>
<td>15–16</td>
<td>Very cold, humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>17</td>
<td>Less cold, humid</td>
<td>4.5</td>
<td>1,099</td>
</tr>
<tr>
<td>18–19</td>
<td>Less cold, humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>20</td>
<td>Mild, humid</td>
<td>21.7</td>
<td>1,395</td>
</tr>
<tr>
<td>21–22</td>
<td>Mild, humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>23</td>
<td>Very cold, very dry</td>
<td>1.2</td>
<td>1,490</td>
</tr>
<tr>
<td>24–25</td>
<td>Very cold, very dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>26–35</td>
<td>Cold and humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>36–37</td>
<td>Cold, very dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>38</td>
<td>More mild, humid</td>
<td>6.9</td>
<td>1,643</td>
</tr>
<tr>
<td>39</td>
<td>More mild, humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>40</td>
<td>Cold and very dry</td>
<td>8.0</td>
<td>491</td>
</tr>
<tr>
<td>41–43</td>
<td>Temperate and humid</td>
<td>3.0</td>
<td>725</td>
</tr>
<tr>
<td>44–49</td>
<td>Cold and dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>50a</td>
<td>Temperate and humid</td>
<td>11.8</td>
<td>678</td>
</tr>
<tr>
<td>50</td>
<td>Temperate and humid</td>
<td>14.7</td>
<td>2,878</td>
</tr>
<tr>
<td>51</td>
<td>Temperate and humid</td>
<td>10.6</td>
<td>1,710</td>
</tr>
<tr>
<td>52</td>
<td>Temperate and humid</td>
<td>15.5</td>
<td>1,255</td>
</tr>
<tr>
<td>53</td>
<td>Cold and humid</td>
<td>29.0</td>
<td>93</td>
</tr>
<tr>
<td>54–55</td>
<td>Cold and humid</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>56–57</td>
<td>Cold and dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>58</td>
<td>Cold and very dry</td>
<td>No data</td>
<td>No data</td>
</tr>
<tr>
<td>59</td>
<td>Less cold, humid</td>
<td>0.0</td>
<td>402</td>
</tr>
<tr>
<td>60–61</td>
<td>Cold and very dry</td>
<td>1.2</td>
<td>1,294</td>
</tr>
<tr>
<td>62</td>
<td>Less cold, humid</td>
<td>0.0</td>
<td>83</td>
</tr>
<tr>
<td>63–64</td>
<td>Cold and dry</td>
<td>No data</td>
<td>No data</td>
</tr>
</tbody>
</table>


Obviously, arguments based on negative evidence are fraught with difficulties, and admittedly, there are many potential explanations—both behavioral and natural—for an absence of evidence for fire in these sites. The hypothesis that this absence is due to an inability to start fires will require quantitative data from many other sites that are adequately dated and for which both indirect and direct evidence for fire is noted (Aldeias et al. 2012; Goldberg et al. 2012; Sandgathe et al. 2011). This is only a hypothesis advanced to explain the cyclical pattern apparent in the data. The more important finding is that fire is not as ubiquitous as it should be, given that virtually all recent hunter-gatherer populations, even prior to access to matches and lighters, used fire daily for a wide range of applications and at almost every location where people spend any time at all. Thus, the main conclusion to be drawn from the evidence at hand is that use of fire by Western European Neanderthals is sporadic at best, and for any particular site—even those with relatively dense or intensive occupations—fire may be virtually absent for long periods of time. What we are suggesting, therefore, is that during the European Late Pleistocene there is simply not enough evidence of fire to assume that Neanderthals used fire, especially for warmth and for cooking, to a degree equivalent to that seen among extant humans. At a minimum, this may mean that fire had a very different role in Neanderthal adaptations in Western Europe than at, say, Kebara, Tabun (Schiegl et al. 1996; Shimelmitz et al. 2014), or Qesem Cave in Israel (Barkai et al. 2017) and that there may have been extended periods of time when fire was not used to a great extent. Thus, the available data we do have for this region of France indicates that Neanderthals were not obligate fire users (contra Sørensen 2017), and such evidence might constitute a significantly different behavioral adaptation than those seen in more recent modern human occupations (see Henry 2017).

Implications for Considering the Role of Fire in Western European Neanderthal Adaptations

The primary focus of this paper is to emphasize the quality of the data presented to show that fire was not present for long periods of time in this particular region. We are not arguing that Neanderthals, as a species, were fire incapable, always ate raw food, and never used fire for heat. Rather we are simply presenting quantitative evidence (rather than simple presence or absence) that at times and for long periods they did not make extensive use of fire. Admittedly, this is based on only a few Middle Paleolithic sites, and given the lack of comparable data available in the literature (see Sandgathe 2017; Sandgathe et al. 2011b; Roebroeks and Villa 2011), it is still unknown to what extent this pattern holds true for many other times and places during the Pleistocene. But the evidence available from a number of sites is strong enough to make us question our assumption that once we find evidence of fire in the archaeological record, it automatically means that it was an essential part of human behavior and adaptation from that point forward (cf. Barkai et al. 2017) and throughout the world.
If this assumption is not valid, and the use of fire was much more limited than previously believed, this does raise important questions regarding European hominin behavior and adaptation in the Pleistocene. One of the more important questions concerns the ability of hominins to survive during the colder periods. Among modern human groups, it would be impossible for foragers to inhabit more northerly latitudes without fire unless they had very well-developed clothing and shelter technology. However, anatomically modern humans are relative newcomers to higher latitudes, unlike Neanderthals who, along with their direct ancestors, have a potential time depth in Europe of several hundred thousand years. While it is possible that Neanderthal populations migrated to some extent in response to major climatic changes and did not always inhabit the most northerly European latitudes during colder periods (e.g., Roebroeks 2006; Steegmann, Cerny, and Holliday 2002), the presence of significant numbers of occupations in Europe during full glacial conditions indicates that Neanderthals were adapted to such conditions.

The question is to what extent was theirs a physiological adaptation versus a cultural or technological one? While we do see the advent of bone needles during the Gravettian of late MIS 3 and early MIS 2, evidence for tailored clothing prior to this is virtually nonexistent (Collard et al. 2016). It has been argued that simply draping or wrapping untailored animal hides around a person has very limited thermal effectiveness (e.g., Gilligan 2007; Wales 2012). Although there is ongoing discussion about how much of the difference in morphology between Neanderthals and their African contemporaries is due to active selective pressures and how much is mainly due to random genetic drift (e.g., Weaver, Roseman, and Stringer 2007), it has long been accepted that Neanderthals have significant cold-adapted features such as their short, squat, heavy bodies with shorter, stockier limbs (e.g., Holliday 1997; Ruff et al. 1993; Steegmann, Cerny, and Holliday 2002; Trinkaus 1981).

Assuming that an absence of fire means an absence of cooking, there are also implications for Neanderthal energetics. This is an area where Neanderthals differed significantly from anatomically modern humans and one with behavioral consequences that may have played a role in the replacement of the former by the latter. It is argued that due to their larger body mass and unique shape, Neanderthals would have had a higher basal metabolic rate than anatomically modern humans and therefore a proportionally larger total energy expenditure (e.g., Aiello and Wheeler 2003; Sorensen and Leonard 2001; Steegmann, Cerny, and Holliday 2002). Conservative estimates suggest a 10% difference between Neanderthals and middle Upper Paleolithic humans (Churchill and Rhodes 2009; Froehle and Churchill 2009; Macdonald, Roebroeks, and Verpoorte 2009). This estimate is based on the premise that Neanderthals and anatomically modern humans derived the same caloric benefits from the food consumed, and it means that if Neanderthals and early anatomically modern humans had the same diet composition, Neanderthals would have been obliged to consume more. This in turn may have necessitated more frequent moves (Macdonald, Roebroeks, and Verpoorte 2009; Verpoorte 2006).

Moreover, given that cooking raises the nutritional and energetic value of food (e.g., Carmody and Wrangham 2009; Wrangham 2009), then an inability to cook their food for extended periods would further increase the amount of calories required by Neanderthals to meet their daily energetic needs. Lower overall energy requirements could have given anatomically modern humans competitive advantages over Neanderthals in terms of reproductive success and demographic expansion (Froehle and Churchill 2009). There is considerable evidence that Middle Paleolithic populations relied particularly heavily on sources of fat in their diet. This is especially apparent in the breakage of long bones, presumably for the extraction of marrow, and the intense, intentional fragmentation of cancellous bone, presumably to extract bone grease (Castel et al. 2016; Hodgkins et al. 2016). In the face of increased caloric requirements for Neanderthals, and especially increased fat requirements, cooking meat may have taken on an especially important role under certain conditions.

Besides increasing net caloric returns, cooking can also reduce the danger presented by bacterial and parasitic loads in meat. As the evidence from sites like Roc de Marsal and Pech IV clearly indicates that meat was not always cooked, it seems likely that consumption of raw meat was relatively common during the Lower Paleolithic and during at least certain periods in the Middle Paleolithic. This might not present any major problems during colder climatic periods when meat acquired by hominins would tend to remain unspoiled longer and, during some cold periods in some regions, was likely more easily acquired and in greater quantities due to the prevalence of large numbers of herd animals like reindeer, horse, and bison. During warmer climatic periods when the fauna was dominated by mainly smaller and less gregarious woodland species (like red deer, roe deer, and wild pigs), meat was likely generally less available (Hodgkins et al. 2016). Meat would also tend to spoil faster during warmer periods, and it is possible that simple meat preservation techniques, like smoking, could have been practiced. However, there is no evidence for such practices, and it may be that, if meat spoilage was a consideration for Neanderthals, they were simply cooking it to make it safe for consumption. Along with increased availability of natural fire, such a pattern of behavior would also help explain the apparent association between increased fire use and warmer climatic periods.

Conclusions

Much of the current evidence suggests that as recently as the latter half of the Late Pleistocene, Neanderthals were not using fire all the time, especially not during cold climatic periods. This raises important questions about how these hominins were able to adapt to high-latitude glacial conditions both in terms of their physiology and their technology.
Roebroeks and Villa (2011) make an important point that there is no evidence supporting the idea that fire was requisite to the initial colonization of Europe. Although they conclude that the use of fire became “habitual” during the European Middle Paleolithic, the data from Roc de Marsal and Pech IV show that hominins occupied or used these sites for long periods of time without using fire. Whether or not these results are applicable to the entire European Middle Paleolithic is currently unknown, since quantified data (rather than simply presence or absence), both direct and indirect, on the degree of fire use is largely unreported (see Sandgathe 2017). The same problem applies to the Upper Paleolithic as well. For a long time, it has been assumed that once the advantages of fire were discovered, its use would spread quickly. But as the evidence is examined more closely, and as we try to evaluate the degree of fire use, it is becoming fair to say that we simply do not know when fire use became a regular, integral, and, eventually, necessary component of hominin adaptations.

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Technologies for the Control of Heat and Light 
in the Vézère Valley Aurignacian

by Randall White, Romain Mensan, Amy E. Clark, Elise Tartar, 
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We can trace the beginnings of our knowledge of early Upper Paleolithic (Aurignacian) use of fire to the pioneering 1910–1911 excavations at Abri Blanchard undertaken by Louis Didon and Marcel Castanet. At Blanchard, the excavators recognized and described fire structures that correspond in many ways to features excavated more recently in Western and Central Europe. Here, we address the issue of heat and light management in the early Upper Paleolithic, demonstrating a pattern that builds on these early excavations but that is refined through our recent field operations. Topics to be discussed include (1) recently excavated fire structures that suggest complex fire management and use, (2) the seemingly massive use of bone as fuel in most early Aurignacian sites, and (3) the anchoring of skin structures for purposes of heat retention with fireplaces behind animal-skin walls. Furthermore, new data on activities around fireplaces make it possible to infer social and organizational aspects of fire structures within Aurignacian living spaces. The vast majority of early Aurignacian occupations, most of them now dated to between 33,000 and 32,000 BP (uncalibrated), occurred on a previously unoccupied bedrock platform into which the occupants dug their fire features.

The use of fire has long been recognized as a key innovation in human evolution as a source of light and heat, a mechanism for cooking (Chazan 2017; Villa, Bon, and Castel 2002; Wrangham 2017), and a focal point for fireside activities and social bonding (Alperson-Afil 2008; Fernández Peris et al. 2010). Often, however, we are overly preoccupied with the earliest occurrences of fire rather than its use in cultures where we have long known controlled fire to be present.

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Our research on classic sites in the Aurignacian shows that not only was fire an essential part of life for human groups during this time but that it was manipulated and used in a standardized and consistent manner within an overarching system of heat and light capture and control. This includes altering the limestone bedrock to create concavities in which the fires sat and the creation of adjacent structures for the control and manipulation of different types of heat (e.g., the removal of hot coals from the primary fire feature to an adjacent location for a special use) and light (portable lamps).

In this paper, we will first present a series of early Aurignacian sites from the Vézère Valley, combining our recent interventions as well as observations from early excavations. A clear pattern will emerge: at site after site, the earliest Aurignacian occupation sits directly on the bedrock, dates to between 32,000 and 33,000 years BP (uncalibrated), and exhibits complex fire structures within human-made depressions in the bedrock. The quality of information for each of these fire structures depends on when they were excavated, but a clear pattern can nevertheless be established. We do have a particularly clear window on this pattern, however, that derives from our recent excavations at Abri Castanet. Between 2005 and 2010 we excavated an interconnected set of fire structures that is testament to the sophisticated management of fire in the Aurignacian. Finally, we will discuss a few key topics relevant to the management of fire, heat, and light in the early Aurignacian. These include the organization of activities around fire structures, use of bone or wood as fuel, and the production of pierres à anneaux, rings carved in the limestone to enclose the rock-shelter with skins and retain heat. Many of our inferences surrounding these topics make use of an abundance of experimental research over the past 20 years that has sought to investigate cultural and natural formation processes of combustion-related features (see, e.g., Aldeias 2017; Costamagno et al. 2010; Lejay et al. 2016; Miller et al. 2010; Théry-Parisot et al. 2002).

Classic Aurignacian Sites of the Vézère Valley and Associated Fire Structures

Abri Castanet and Abri Blanchard

When Marcel Castanet discovered a complex of fire features at Abri Blanchard in May 1910, he and his employer, Louis Didon, were ill equipped to understand the importance of this find, and given the state of knowledge before World War I, they had few points of comparison. Castanet drew a rough sketch in plan view (fig. 1), and after having recovered many spectacular artifacts associated with these fire features, he simply backfilled the entire area containing the fire pits. Nearly 6 months later, in October 1910, Didon asked Castanet to reexpose the fire structures so that he could observe them himself. While there are allusions to photographs taken by Didon, these appear not to have survived. The only record is that plan view sketched by Castanet on May 21, 1910 (fig. 1), which shows one large elongate feature and three smaller satellite features all dug into the friable limestone bedrock.

![Figure 1. Castanet's May 21, 1910, plan view of the fire features at Abri Blanchard, annotated and translated. L. Didon archive (cf. Delluc and Delluc 1978). A color version of this figure is available online.](image-url)
In the Blanchard publication, Didon (1911) described the fire features as follows.

The four hearths were constituted of shallow pits dug into the bedrock terrace. Three of the pits were circular, with an approximate diameter of 0.5 m and a depth of 0.2 m. The fourth, rectangular with semicircular extremities, measured 3.5 m long by 1.5 m wide, with a depth of ca. 0.4 m. They were filled with ash and calcined bone. Because of the thickness of this layer, the ashes seemed to date to the previous day, and certain blocks of the material, a sort of breccia composed of ashes and conglomerated bones, were really impressive. I kept one of these blocks, and it was as if one needed simply to blow on it to revive the fire that had been extinguished so many centuries ago.

Didon describes these remarkable breccia-like blocks with greater detail in a letter to Breuil in February 1911, 4 months after the pits had been reexposed by Castanet.

Yesterday, I retrieved from a case some hearth fragments. I use the term “hearth” in the usual sense of the word because these are far from being simple chunks of breccia. One block, 30 x 12 cm, was composed of large fragments of carbonized bone and reindeer antler with ashes adhering to them. It seemed as if one simply needed to blow on them to reignite the fire; it is very impressive. I retrieved them from the depressions dug into bedrock (by the Aurignacians).¹

Beginning in 1911, Denis Peyrony employed Marcel Castanet to excavate the Abri Castanet, situated on the same bedrock platform just 50 m to the south of Abri Blanchard. At Abri Castanet, as at Abri Blanchard, the Aurignacian I layer (Peyrony’s layer A) sat directly on bedrock. Following the excavation of this layer, Peyrony (1935) described and illustrated precisely the same kinds of fire features dug into the bedrock as those found at Abri Blanchard (see fig. S1; figs. S1–S15 available online). He observed four features, one of them 1.3 m long. He noted, as had Didon before him, that the most spectacular artifacts were concentrated around these fire features. At Blanchard, this Aurignacian I layer has now yielded to our team two hydroxyproline dates on mammal bone of 33,420 ± 350 and 33,240 ± 360 BP (uncalibrated; Bourrillon et al., forthcoming), and at Castanet, 15 ultrafiltration dates on bone give an average age of 32,400 BP for the same layer (White et al. 2012). We will return to Castanet later in this paper to describe our recent excavation of four such fire features within the previously unexcavated southern portion of the site.

La Souquette

Blanchard and Castanet are situated at the base of the cliffs on the eastern slope of the small Castel-Merle valley. The opposing western side of the valley has also yielded a rich early Aurignacian site, the Abri de la Souquette, just 50 m across the valley from Abri Blanchard. Unfortunately, because of late medieval quarrying and massive pillaging at the beginning of the twentieth century, only a small fragment of the site was available for modern excavations by Roussot (1982) in the 1980s.² Roussot observed and excavated a few square meters of the Aurignacian I level, situated directly on bedrock (see fig. S2).

We have been able to analyze and date this early Aurignacian assemblage, which is virtually identical in its contents (typologically, technologically, artistically) to Blanchard (lower level) and Castanet (lower level in the northern and southern sectors). Although no preserved fire features were discovered in the small area of Roussot’s excavations, reindeer bone fragments from this level yielded molecular ultrafiltration dates of 32,400 ± 500 BP and 32,150 ± 450 BP (dates uncalibrated; O’Hara et al. 2015). This information from La Souquette reinforces the pattern that in the Vézère Valley, the first Aurignacian I occupation occurred directly on bedrock and dates to around 32,000 BP uncalibrated.

Abri Cellier

In the summer of 1927, George Collie from Beloit College, Wisconsin, undertook excavations at Abri Cellier (Collie 1928; White and Knecht 1992) near Le Moustier in the Vézère Valley. Although there is some stratigraphic confusion (White 1992; White and Knecht 1992), our return to the site in 2014 did much to clarify the situation (figs. 2, S3; White et al., forthcoming). As at Abri Castanet and Abri Blanchard, the initial occupation of the site by early Aurignacian groups was on an exposed bedrock platform. It was only late in the excavation that Collie recognized bedrock at the site and thus did not clearly observe related fire features. In cleaning the bedrock surface in 2014, we were nonetheless able to observe fire-reddened depressions (cuvettes) on the surface of the bedrock and were even able to excavate highly calcined deposits within a residual fire pit feature preserved in a deep hollow in the bedrock (fig. 3). Bone from this structure yielded an ultrafiltration date of 33,600 ± 550 BP (White et al., forthcoming). We were struck by the similarity of the Cellier features to those described at Blanchard and especially to those described by Peyrony (1946) and excavated by us at Abri Castanet.

Abri Pataud

In his excavations at Abri Pataud, Movius (1966) paid particular attention to fire features. Those in layer 14, situated directly on bedrock, are indistinguishable from those described above in having been excavated into the bedrock platform (fig. 4). Other sites in the Vézère have yielded the same pattern of occupation by Aurignacians directly on bedrock with instal-


lation of fire features directly on or in the fractured and spalled limestone surface (Delporte 1968). However, we have restricted our discussion here to those with which we have personal experience. It is worth noting, however, that where the early Aurignacian is followed by later Aurignacian levels within the same stratigraphic sequence, such as at Abri Pataud and Abri du Facteur, there is significant change through time in hearth structure (e.g., cobble lining) and arrangement (Delporte 1968; Movius 1966).

Returning to Castanet

Our own excavations at Abri Castanet between 2005 and 2010 focused on what appeared at first to be a massive and diffuse fire feature (stratigraphic unit 109) that resolved into three separate features as we descended through the layer (the equivalent of Peyrony’s layer A; fig. 5). All three of these features were excavated by the Aurignacians into the bedrock platform by removing a number of plaquettes of which the bedrock is constituted. These three features are named Structures 216, 217, and 218 (see fig. S4).

Excavation Strategy and Techniques

The meticulous, but routine excavation of the overlying, undifferentiated black stratum (our US 214), allowed us to identify a spatially extensive (ca. 2.6 m²) feature, which seemed at first encounter to be either (1) several adjacent fire structures, (2) a single combustion feature having been subjected to post-depositional alteration, (3) an ash dump, or (4) all of these at the same time.

In order to evaluate the relative merits of these different hypotheses, we moved from excavation in .25 m² units to a .0625 m² grid. We sought to sample and provenience all the fine-fraction bulk sediment in order to record, quantify, and situate in three-dimensional space all of the products and residues of combustion. Our objective was to treat raw sediment samples in the laboratory in order to detect, recover, and study microvestiges of combustion such as charcoal, burned bone, and phytoliths.

In complement to the recovery of bulk sediments, we undertook the extraction, embedding, and micromorphological study of oriented blocks of in situ sediment. Micromorphology sought an understanding of the microstratigraphic context of each sample and a characterization of the taphonomic processes underlying the nature and distribution of macromicrovestiges recovered from the raw sediments.

As we descended through the fire feature, it became apparent that the diffuse black deposit (our stratigraphic unit 214) resolved into three observable structures, which we labeled 216, 217, and 218. We continued to employ the same fine-grained procedures but now carefully separated the bulk samples from adjacent structures 217 and 218. Structure 216 posed special problems because it contained little sediment, and its heavily calcined bone infilling did not
Figure 3. Abri Cellier, cleaned bedrock with small fire pit adjacent to two large fire-reddened depressions excavated by the Aurignacians into the underlying bedrock. A color version of this figure is available online.
permit normal excavation because osseous tissue simply fell to dust under the slightest tool contact. The decision was made to remove the entire contents in bulk, again controlling the microstratigraphy with micromorphological samples.

Magnetic Susceptibility

In 2010, we performed magnetic susceptibility analysis (Brodard et al. 2016; Lecoanet, Léveque, and Ambrosi 2003; Lecoanet, Léveque, and Segura 1999) of the excavated area, including the observed combustion features. One of the objectives of mapping the magnetism of the substratum and immediately overlying deposits is to distinguish between zones where combustion occurred in situ and those of secondary deposition. Because the underlying Coniacian bedrock showed virtually no magnetic signal, the surprisingly intense magnetic signal observed at Castanet had to emanate from the structures’ infilling. Our microvestige analysis of the fire features’ contents enabled us to demonstrate that each of the three structures contained high frequencies of iron oxides and kaolinite at both microscopic and macroscopic scales. During combustion these were transformed to magnetite and took on the prevailing planetary magnetic field. The three structures appear to be contemporaneous and to have functioned more or less independently. Some of the conclusions of the magnetic analysis will be presented below.

Structure 216

This small fire feature, dug into the bedrock platform, was roughly 30 cm in diameter with a maximum depth of 20 cm. It contained a dense deposit of burned and calcined bone with no interstitial sediment except some heat disaggregated limestone bedrock.

Structure 216 contained only 29 lithic pieces, two of which refit with a piece from Structure 218. All three are fire exploded. Another piece refits with six others from outside the fire features per se. All seven pieces are products of the creation of a carinate scraper/core blank (Chiotti and Cretin 2011). The constituents of both of the above refits are from the same block of flint.

The infilling is identical to that of Structure 217 with respect to oxidized residues, but the magnetic signal is less intense, leading to the suspicion that the contents of Structure 216 were extracted from Structure 217 while still hot. At its summit, this fire feature had a large portion of a burned bovid horn core (visible in fig. S5). Observations at all scales converge to suggest that the nature and function of this feature are radically different from Structures 217 and 218. In its absence of sediment and dominance of burned/calcined bone, Structure 216 resembles very closely the small fire features with “breccia” described by Didon at Abri Blanchard, and it is very similar to residual structure 1 from Abri Cellier.

Structures 217 and 218

Structure 217 is a roughly circular structure with a diameter of ca. 0.6 m, bordered on the west by six vertically arranged plaquettes that close off the northwest side of the structure the margins of which are otherwise formed by the contours of the depression dug into bedrock by the Aurignacians. Two profiles excavated into structure 217 show its infilling and topography (see fig. S7). It contained 64 lithic pieces, none
Figure 5. Castanet southern sector with “footprints” of three distinct fire features after excavation. Grid in square meters divided into one-quarter square meters. A color version of this figure is available online.
refitting with the other fire structures. All other refits were internal to one of the fire structures.

Magnetic susceptibility and micromorphology (see figs. S8–S10) indicate that Structure 217 is relatively well preserved and that combustion took place there. In contrast, Structure 218 is magnetically heterogeneous, suggesting that the contents are not at the site of original combustion. Possibilities include an ash dump or an overflow of ashes and combusted material from Structure 217 that were subsequently subjected to trampling (see Schiegl et al. 2003). Curiously, 217 and 218 each had an unburned cervid mandible on their upper surfaces. Structure 217 that were subsequently subjected to trampling

The surface excavated by us at Castanet amounts to about 30 m². Examples of Osseous Industry and Ornaments

Activities Concentrated around the Fire Features: Examples of Osseous Industry and Ornaments

The surface excavated by us at Castanet amounts to about 30 m². A single level is present. This layer is dense with faunal remains, debris from the final stages of production of lithic and osseous tools, fragments of colorants such as ochre and hematite, and debris from the production of personal ornaments. Much of this constitutes the refuse from a diversity of activities that took place around the fire features. As is the case for many Paleolithic and ethnographic sites (Binford 1998; Gamble 1991; Hahn 1988; Miller et al 2010; Rigaud and Simek 1991; Stapert 1989; Surovell and Waguespack 2007; Vaquero and Pastó 2001), the fire features at Castanet served as a focal point or “tether” for activities within the site.

It is noteworthy that carinate scrapers/bladelet cores were produced around these fire features (Chiotti and Grotta 2011), and resulting microbladelets are abundant. However, the blades and flakes that served as blanks for these and other retouched lithic tools were produced somewhere outside of the excavated area. Not a single flint blade or flake core has been recovered from the 30 m² excavated area of the southern sector of Abri Castanet. The act of blade/blade production, resulting in messy and dangerous by-products, seems to have been excluded from the living space immediately surrounding the Castanet fire features.

Two activities exemplify this pattern: osseous tool/weapon manufacture and use, and personal ornament manufacture and use. It is particularly interesting to contrast the spatial location of formal finished artifacts and their production debris.

Osseous Tool/Weapon Manufacture and Use

Observed patterns in the distribution of different formal categories of osseous tools, weapons, and debitage and the distribution of burned and unburned osseous pieces almost certainly reflect functional differences among fire features and the spatial organization of different activities associated with them. Fine-grained proveniencing permits a number of specific observations.

Almost all formal osseous artifacts are situated outside the perimeter of the three combustion features 216, 217, and 218 (fig. 6), and none are burned. Split-based antler points and the tongued pieces related to their production (Tartar and White 2013) are concentrated to the south of these features. Smoothers (lissoirs) are concentrated at the northeastern margins.

Bone retouchers, intermediate tools such as wedges and chisels, as well as bone and antler waste and debitage products bearing technical stigmata show no special distribution (apart from four retouchers found adjacent to the 1995–1998 fire feature 1). Some of these objects are found outside of the fire structures per se but within the perimeter (near its eastern limit) of the diffuse cloud of black sediment (US 109) encountered in descending through the layer (dotted outline on fig. 6) before the three fire features revealed themselves.

Small burned pieces of antler (N = 55) showing no technical traces are abundant in both Structures 217 and 218 as well as in the area just to their north, but they are entirely
absent from Structure 216. The abundance of these nondietary faunal remains in Structures 217 and 218 might result from the first steps of antler exploitation that were somehow linked to these structures. If so, Structure 216 was not involved in such activities.

**Personal Ornament Manufacture and Use**

The distribution of objects linked to personal ornaments and their production is equally suggestive. Raw ivory fragments imply the on-site reduction of large chunks of subfossil mammoth tusks. The creation of usable blanks by direct percussion and torsion of fragments of old tusks seems to have been the objective. The morphology of the by-products of this percussion varies from small flakes and splinters from the external tusk layers to angular fragments of complex morphology emanating from direct percussion of the interior parts of already desiccated tusks. Fresh tusks cannot be worked in this way. The spatial distribution across the entire excavated area (fig. 7) is consistent with fragments being projected during high-impact direct percussion (Heckel and Wolf 2014).

Farther along the bead production chain, unfinished bead stages have a different distribution, with important concentrations to the north and west of the Structure 216, 217, 218 perimeters. Both raw ivory fragments and unfinished production stages show concentrations in square H12, while that square does not contain a single finished bead (fig. 7).

Finished, unbroken beads show two hot spots, one to the north of 217–218 and the other toward the southeastern extremity of the excavated area (fig. 7). Broken, finished beads (not shown) have a broader distribution, suggesting loss due to breakage during use.

The spatial organization of the two examples presented here, osseous technology and personal ornaments, indicate that some spatial patterning between production debris and finished products can be observed around the fire features at Abri Castanet. The presence of both production debris and finished products indicates that the fire features were a focal...
Figure 7. In all cases the grid is in square meters divided into subsquares of one-quarter square meter. Top left, Abri Castanet, southern sector, 1995–2010. Shading indicates frequency per one-quarter square meter of raw ivory fragments. Top right, Abri Castanet, southern sector, 1995–2010. Distribution of stages 1–4 of the basket-shaped bead production chain. Shading indicates frequency per one-quarter square meter of unfinished objects. Bottom, Abri Castanet, southern sector, 1995–2010. Spatial distribution of finished ivory basket-shaped beads including fragments. Shading indicates frequency per one-quarter square meter of finished beads. A color version of this figure is available online.
point for a diversity of activities that were concentrated around its borders.

Use of Bone as Fuel

Early Aurignacian sites in southwest France are famous for yielding very high frequencies of burned and calcined bone with relatively little wood charcoal being present (Costamagno et al. 2005; Marquer et al. 2010; Théry-Parisot 2001, 2002; Théry-Parisot et al. 2002). While this has often been interpreted as reflecting an emphasis on bone as fuel in Pleistocene landscapes where tree cover is minimal, the link to low tree-cover environments is not always agreed on.

Microcharcoal analysis (Marquer 2010; Marquer et al. 2010, 2015) of the Castanet fire feature contents provides new insights into the observed predominance of bone and scarcity of wood charcoal there. In fact, controlled sieving of the fire feature contents yielded an abundance of microscopic wood charcoal (microscopic charcoal results from combustion processes and secondary fragmentation of macroscopic charcoal), almost all of it with a particle size of less than 63 μm (fig. 8). Therefore, while bone was certainly used as a fuel at Castanet, the abundance of wood charcoal at smaller particle sizes indicates that wood played a much more important role than was previously assumed. In sum, wood charcoal appears to be invisible to the usual array of recovery techniques because of taphonomic or cultural processes that remain to be determined (Marquer et al. 2010, 2012).

The pattern found at Castanet does not necessarily extend to all early Aurignacian sites; although Marquer et al. (2010) found an abundance of microscopic charcoal at Abri Pataud, burned bone still dominated all size fractions (Marquer et al. 2010). Bone, however, is less susceptible to taphonomic processes than is charcoal (Marquer et al. 2010), and based on rates of bone combustion established by experiments performed by Théry-Parisot (2002), an overly high dependence on bone as fuel would result in the improbable situation of humans hunting to feed the fire. It cannot be assumed that bone was more plentiful than wood in the environment; indeed, neither were plentiful, and Aurignacians likely exploited any and all fuel sources available to them. It is therefore most likely that both wood and bone were utilized as fuel in ratios that varied by availability but that, in general, the use of wood in early Aurignacian sites is underestimated.

Heat and Light Capture and Retention

Maximization of heat and light would have been beneficial to Upper Paleolithic hunter-gatherers in the late Pleistocene lower latitudes of late Pleistocene Europe. It has long been recognized that in the Vézère Valley, the very placement of their occupations (see fig. S12) was an accommodation to these concerns (White 1983, 1985). While the advantage of solar energy capture on south-facing cliff faces is significant (Bouvier 1967; Legge 1972), it should not be forgotten that at the latitude of the Dordogne, winter days are short (8 hours, 47 minutes of daylight at the winter solstice compared to 15 hours, 35 minutes at the summer solstice), and south orientation would have provided maximum daily light.

A common occurrence in Vézère Valley early Aurignacian sites is that of so-called pierres à anneaux, limestone blocks and slabs with a distinctive form of a carved ring. Castanet, Blanchard, La Souquette, Cellier (fig. 9), and Pataud have all produced these. At Blanchard and Castanet, these were observed to be concentrated along the supposed original drip line of the shelter (Didon 1911; Peyrony 1935). In the last year of excavations at Castanet, we too found anneaux in the rubble of the collapsed drip line of the shelter.

We have been able to demonstrate as well that these labor-intensive features were also placed on freestanding blocks on the living surface of the site. Our experiments show that these rings withstand very little force, strain, and stress, and we also know from our analysis of site formation that the ceiling of the shelter was approximately 2 m above the occupational surface.

Figure 8. Numbers of fragments and particles of charcoal and burned bones and their ratios relative to size classes of the recovered samples.

These data and observations incline us to support Denis Peyrony’s old hypothesis (Peyrony 1935) that the *anneaux* served to guide and suspend animal skins from the drip line of the shelter in order to retain heat, to reflect heat and light back into the shelter, and to serve as a windbreak vis-à-vis westerly and northwesterly winds entering from the front of the shelter. Moreover, new seasonal data, based on cementum annuli analysis (Naji, Gourichon, and Rendu 2015; Rendu 2007, 2010) of reindeer and horse teeth, are categorical; Castanet was an exclusively cold season occupation (figs. 10, S13).

The southern sector of Abri Castanet has also yielded a fat-burning lamp, associated with Structure 218, which would have complemented and rendered portable the light provided by the fires (see fig. S14). Such portable light technology (de Beaune and White 1993) would have allowed the Aurignacian occupants of Castanet to better adapt to long winter nights and to the darkness of the enclosed living space and the outside surroundings.

**Régismont-le-Haut, a Point of Comparison for the Vézère Valley Sites**

Régismont-le-Haut (Poilhes, Hérault) is one of the rare open-air Aurignacian sites to have yielded well-preserved evidence of the organization and arrangement of living space separated into distinguishable activity areas (Bon and Mensan 2007).

The site has been the object of long-term, programmed excavations by one of us (RM) since 2000. In the course of this research, 28 combustion features have been excavated, concentrated in two paleochannels that served to shelter the Aurignacian occupants. Around these fire features are dense concentrations of archaeological material reflecting functionally complementary poles of activity.

Two primary zones have been identified, one in each of the perpendicularly oriented paleochannels. The first contains several vast multifunctional structures that we interpret as belonging to a “domestic area.” The second is constituted of several structures of a more specialized nature that we interpret as a “workshop area.”

The principal domestic area is organized around a concentration of three fire structures. These are three pits, two of which are characterized by intense traces of combustion (12 and 16) and the third showing brownish impregnations and an infilling of burned bones (see fig. S15). This organization is strikingly similar to that of the southern sector of Abri Castanet. The archaeological material associated reveals a range of activities such as bladelet production, tool recovery, and bone working.

4. For example, A. Pike-Tay’s unpublished manuscript, 2000, “Dental growth mark analysis of Rangifer tarandus and Equus of Abri Castanet.”

5. The lithic industry is rather original compared with other assemblages available for comparison, making chronological attribution difficult. Attempts to date the site radiometrically (Bon 2002) do not allow attribution to a particular Aurignacian phase. It could be a regional facies of the early Aurignacian or a previously unobserved variant of a later Aurignacian.
sharpening, and the processing of mineral pigments as at Castanet.

At Régismont, all of the combustion features and surrounding concentrations of material culture are attributed to a single, spatially continuous occupational surface. The redundancy in the spatial organization and association of different groups of structures such as the one described above sustains the hypothesis of a single episode of occupation that took the form of a vast seasonal residential camp. The careful observation and documentation of the internal organization of the site around combustion features makes Régismont-le-Haut a key point of comparison for the Aurignacian record of the Vézère Valley (Anderson et al., forthcoming). That comparison leads us to propose that the redundant fire feature organization that we observe in the Vézère was the expression of a geographically widespread characteristic of Aurignacian culture.

Conclusions

Using both old archives and the new methods and data available to us, we are beginning to be able to address important questions of heat and light management in the early Upper Paleolithic. In one region, the classic Vézère Valley of southwest France, we have seen the existence of complex and diverse fire features that require excavation and analysis with forensic precision. The kinds of fire features and their arrangement across living surfaces repeat from one site to the next and may well be part of a broader European pattern. We maintain that fire was manipulated and used in a standardized and consistent manner within an overarching system of heat and light capture and control.

A remarkable aspect of the early Aurignacian record in the Vézère Valley is that we can follow particular fire features across a time horizon marked by the availability for occupation of bare bedrock terraces in the period between 33,000 and 32,000 BP (uncalibrated). Early Aurignacians, moving directly onto the previously unoccupied bedrock, dug their fire pits directly into the substrate. This seems to have been a characteristic of the early Aurignacian only; cobbled-lined or bordered fireplaces show up and become dominant in later stages of the Aurignacian.

The fire features themselves also display a very consistent pattern. The fire complex that we excavated at Abri Castanet (consisting of Structures 216, 217, and 218) demonstrates a fire use that was intensive and easily adaptable to many specialized functions. Given that Castanet was a winter occupied site, the fire in Structure 217 could have burned more or less continuously, with its contents subsequently moved to Structures 216 and 218 for cleaning or for tasks that required the control of heat and flame. A nearly identical arrangement of fire features found at Abri Cellier reinforces the view of a highly systematic management of fire in the early Aurignacian.

Evidence from Abri Castanet suggests that while these fires were fueled to a certain extent by bone, wood played a very important role, one that is probably significantly underrepresented because of taphonomic processes. Provisioning the site with enough fuel to feed these intensive fire complexes would have come at a significant economic cost.

The hypothesis of the anchoring of skin structures within rock-shelters for purposes of heat retention, with fireplaces behind animal-skin walls, was made first in 1935 by Peyrony (1935). Our recent research supports this hypothesis. It is worth asking whether this is a seasonal phenomenon, as it is now clear that Abri Castanet was an entirely cold season occupation.

New robust data on activities around fireplaces at sites like Castanet make it possible to infer social and organizational aspects of fire structures within Aurignacian living spaces. The spaces created within these Aurignacian sites, combining complex fire structures, anneaux for enclosing the rock-shelters with hides, and engraved and painted artwork on the walls and ceilings (White et al. 2012) would have been extremely important sanctuaries for the protection from the cold and the extension of daylight hours.

During the cold winter evenings, when daylight departed early, Aurignacian groups would have been able to continue to make beads, produce and maintain their tools and weapons, process pigments, prepare meals, and strengthen social bonds through fireside talk (Dunbar 2014; Wiessner 2014). This warm and protected space would have given these groups a powerful advantage and may explain why Aurignacian peoples seem to have thrived in the glacial conditions of late Pleistocene France.

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Control of Fire in the Paleolithic
Evaluating the Cooking Hypothesis

by Richard Wrangham

According to current evidence, *Homo sapiens* was unable to survive on a diet of raw wild foods. Because cooked diets have large physiological and behavioral consequences, a critical question for understanding human evolution is when the adaptive obligation to use fire developed. Archaeological evidence of fire use is scarce before ca. 400 ka, which suggests to some that the commitment to fire must have arisen in the mid-Pleistocene or later. However, weak jaws and small teeth make all proposals for a raw diet of early Pleistocene *Homo* problematic. Furthermore, the mid-Pleistocene anatomical changes seem too small to explain the substantial effect expected from the development of cooking. Here I explore these and other problems. At the present time no solution is satisfactory, but this does not mean the problem should be ignored.

In this paper I consider the current status of the cooking hypothesis. I use “cooking” to mean the processing of food with heat. The cooking hypothesis posits that control of fire leads to such a large increase in energy acquisition and reduces the physical challenges of eating food so greatly that the evolution of an obligation to incorporate cooked food into the diet should be recognizable by evidence of novel digestive adaptations and increased energy use. It also claims that the only time in the fossil record when the appropriate changes are seen is the early Lower Paleolithic (Parker et al. 2016; Wrangham 2006; Wrangham and Carmody 2010; Wrangham et al. 1999).

The evidence for Lower Paleolithic control of fire has been increasing in the last decade (Alperson-Afil 2008; Berna et al. 2012; Bosinski 2006; Walker et al. 2016). Nevertheless, numerous archaeological sites before the Upper Paleolithic challenge the cooking hypothesis because they find no evidence for the control of fire. European Lower Paleolithic sites such as Dmanisi, Atapuerca, La Caune d’Arago, and Boxgrove represent in total a screening of thousands of unburned bones but no burned bones (Gowlett and Wrangham 2013). Even in the Middle Paleolithic many Neanderthal sites have no fire evidence (Sandgathe et al. 2011a, 2011b). Outside Europe, the few cases where preservation conditions allow long sequences also offer puzzles. Tabun and Qesem caves lie near the Mediterranean coast about 100 km apart. In Tabun, cave fire use was “regular or habitual” by 350–320 ka, but burned flints were scarce or absent during at least 50 ka of prior occupations (Shimelmitz et al. 2014). In Qesem, by contrast, the evidence of fire use is impressive back to 420 ka (Barkai et al. 2017).

One interpretation of such cases is that absence of evidence really is evidence of absence. The implication is that populations of *Homo* occupied Europe during the Lower Paleolithic and later without the systematic control of fire, surviving on raw food for hundreds of thousands of years (Roebroeks and Villa 2011; Shimelmitz et al. 2014). Alternatively, the archaeological visibility of fire may vary too much to allow the history of its control to be confidently reconstructed. For example, Boxgrove was a damp shoreline site that might have been unsuitable for locating fire. Changes in the style of fire use over time could have biased preservation. Middle Paleolithic fire sites might have been larger, or more permanent, or sited more often in caves than in earlier times (Gowlett and Wrangham 2013). For these reasons the debate over the meaning of *Homo* sites that lack any evidence of fire is unresolved, and I will not discuss it here.

I consider instead some conceptual and empirical challenges arising from the assumption that cooked food did not become obligatory until the mid-Pleistocene. The evolution of *Homo erectus* is often discussed without mentioning the control of fire (e.g., Antón and Snodgrass 2012; Hardy 2009; Isler and van Schaik 2012; Potts 2012). The implication is that either a later time can be confidently found for the origin of obligatory fire use, or fire control has only small effects on human adaptation, or both. But those implications are rarely considered carefully. I suggest that they are wrong.

Here, therefore, I assess the difficulty of understanding a date later than the origin of *H. erectus* for when cooking might have become obligatory. In the first section I review the current status of the cooking hypothesis. I then consider some difficulties that follow from the assumption that *H. erectus* could not cook. Finally, I consider problems for the cooking hypothesis.

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Current Status of the Cooking Hypothesis

Adaptation to Cooked Diets

The cooking hypothesis starts with the claim that unlike other animals, Homo sapiens has evolved an obligation to include cooked food in the diet such that we cannot live without it. The idea has been intimated for at least half a century (Brace 1995; Coon 1962; Symons 1998) and directly supported more recently (Wrangham and Conklin-Brittain 2003).

Key evidence comes from research on raw foodists, that is, people who live for long periods on all-raw diets. Raw-foodist groups typically live in industrial societies on store-bought foods. Even though raw foodists take little exercise compared with hunter-gatherers and have fewer disease challenges, on average they experience chronic energy shortage leading to low body mass index (BMI). In the only study of reproductive performance, incompetent or absent ovulation left more than 50% of women on an all-raw diet unable to reproduce (Koebnick et al. 1999).

These physiological detriments are striking because the diet eaten by raw foodists is extremely high quality compared with any known hunter-gatherer diet (if their diet were eaten raw). Most of the raw foodists’ diet is rich in digestible energy and low in structural fiber because it comes from domesticated species. Furthermore, raw foodists typically process the food extensively by nonthermal means (such as by blending) and (in spite of their supposed adherence to raw) often use heat to lightly cook (up to around 114°F). In addition, raw foodists experience no important seasonal energy shortages (because they buy from globally connected markets; Wrangham 2009).

Low meat intake does not account for the problems faced by raw foodists. No relationship has been found for raw foodists between BMI and the amount of meat eaten (Koebnick et al. 1999). Unlike meat-eating raw foodists, vegetarians eating raw foodists indicates that cooked food provides higher net energy gain than raw food. Feeding experiments with mice support this prediction for all three major macronutrients, that is, long-chain carbohydrates, proteins, and (plant) lipids (Carmody, Weintraub, and Wrangham 2011; Groopman, Carmody, and Wrangham 2015). On raw diets (sweet potato tuber, meat, or peanuts) mice typically lose weight, whereas on cooked diets they maintain weight.

One reason is that digestibility is increased. With regard to starch, ileostomy experiments with five domesticated plants (oat, wheat, plantain, green banana, potato) eaten by humans indicate that cooking raises starch digestibility in the small intestine by amounts that vary across foods from 28% to 109%. On the conventional assumption that because of fermentation by the microbiome, 50% of starch energy is recovered from the colon, the median increase in net energy gained is 30.2% (Carmody and Wrangham 2009).

Schnorr et al. (2015) and Henry (2017) noted that the effects of cooking in human evolution are best studied in wild plants roasted on open fires rather than in domesticated plants cooked with contemporary methods. They assessed the energetic effect of brief roasting times (average 8.7 min) on four species of tuber eaten by Hadza. Three of the species were normally cooked, and one was normally eaten raw. Schnorr et al. (2015) found that such cooking led to much variation in the in vitro starch digestibility both within and between species. In two species, cooking led to a 10% increase in glucose availability, whereas in the species typically eaten raw (Ipomoea transvaalensis), glucose absorption fell after roasting. Schnorr et al. (2015) concluded that starch gelatinization is not necessarily a route by which cooking increases net energy gain. Instead, after finding that brief periods of roasting made tubers much easier to chew, they suggested that cooking could increase net energy gain by making chewing more efficient. Cooking also makes tubers easier to peel, which Henry (2017) suggested was its main benefit. Such experiments are promising, but as Schnorr et al. (2015) noted, they are at an early stage because they have considered only glucose, they have not taken account of variation in quality within food species, and they rely on in vitro measures of digestibility.

Other energy benefits of cooking have been less well quantified. They include a reduced cost of digestion (snakes: Bo-back et al. 2007; rats: Carmody 2012), shorter and less vigorous chewing times (humans: Zink, Lieberman, and Lukas 2014), increased chewing efficiency (Dominy et al. 2008), and reduced investment in immune defenses when meat is eaten (Carmody and Wrangham 2009; Carmody et al. 2016). In addition, cooked food is more quickly digested than raw food, which means that if extra food is available, the total rate of energy acquisition per day can be higher.

In the case of plant lipids, a principal mechanism by which cooking increases digestibility concerns the common way in which they are stored in oilseeds. Oilseed lipids are stored in oil bodies surrounded by proteins called oleosins that present a hydrophobic interior surface and a hydrophilic exterior. Cooking denatures the oleosins and thereby makes the lipids available for faster digestion (Groopman, Carmody, and Wrangham 2015).

How Does Cooked Food Benefit Consumer Physiology?

Evidence of BMI reduction and reproductive problems among raw foodists indicates that cooked food provides higher net energy gain than raw food. Feeding experiments with mice...
No tests of the effects of cooking on energy gain have yet been conducted with animal lipids, which are mostly stored as droplets inside adipocytes or other cells. The lipid droplets of vertebrates and insects are coated with proteins of the perilipin family (Arrese and Soulages 2010; Brasaemle 2007). The effect of heat on denaturation of perilipins appears to be unknown. The physical effect of heating solid fats to liquid forms or thin layers could be important in promoting release of lipids from adipocytes. Furthermore, the thinning of fats into oils could facilitate more rapid digestion given that digestive lipases are active only at oil-water interfaces, where they depend for their effectiveness on lipids presenting a high surface area (Lentle and Janssen 2011). How much such effects matter is unknown. There are numerous ethnographic reports of eating raw animal fat (Ben-Dor, Gopher, and Barkai 2016). Variation in fat type could be important. It might be more beneficial to cook lipids that have high melting points.

The uncertainty about effects on animal-sourced lipids as well as limited experimental study for all macronutrients mean that the energetic effect of cooking is not well quantified. Progress in solving this problem will be slowed by numerous sources of variation, including the physical states of the diet, such as whether it is eaten cold or hot, blended or whole, mixed or pure, and fresh or fermented. However, even though the energy gain from eating food cooked is poorly known, there are clear indications that the amount is large enough to have major fitness consequences. The figure of 30.2% increase for starch may well be on the low side because it is derived solely from considering digestibility, excluding reduced costs of digestion, increased food safety, and reduced time digesting. Effects of cooking a starch-rich food appear broadly similar to those for cooking protein-rich food (meat) and lipid-rich food (nuts; Groopman, Carmody, and Wrangham 2015). Thus, a 30% gain in energy seems a reasonable starting point for considering the effect of cooking.

Much smaller increases in energy have large fitness effects in the wild. When chimpanzees of the Kanyawara community in Kibale National Park, Uganda, were able to eat 5% more fruit in their diet than usual (thanks to improved fruit availability), they experienced a 4-month reduction in waiting time to conception (Emery Thompson and Wrangham 2008). Numerous similar examples in large nonhuman primates indicate that even modest increases in net energy gain have substantial positive effects on fitness. The estimated 30% increase in calorie gain is therefore comparatively massive. It is also exceptional because compared with many changes in diet (e.g., addition of fat-rich meat), it works both during periods of food scarcity and during periods of abundance.

Could Homo sapiens Live without Cooked Food in the Wild?

No human populations are known to live without cooking, but might it be possible? Luke Glowacki (personal communication) observed that unmarried Nyangatom men in cattle camps in southwestern Ethiopia sometimes spend several weeks or a few months living solely on raw blood and milk. While this diet leaves the men thin, it raises the question of whether African populations of *H. sapiens* might have been able to survive on a diet that was sufficiently focused on equivalently fat-rich and easily chewed raw wild foods, such as oilseeds, marrow, brains, or guts.

In African habitats, seasonal variation is a problem for both oilseeds and marrow (Speth 2010). Oilseeds can be vanishingly scarce, while the fat content of herbivore marrow declines from more than 90% dry weight at the best time of year to 2%–3% at the worst (late dry and early wet seasons; Dunham and Murray 1982; Lupo 1998). So oilseeds and marrow are unreliable year-round sources of energy (Speth 2010).

However, brain fats are never depleted, remaining around 50%–60% dry weight all year (Carlson and Kingston 2007; Stiner 1994). So conceivably a sufficient abundance of brains could give modern humans the basis for surviving as wild raw foodists during food-scarce seasons. How much brain would be required is, therefore, an interesting question. If the diet needs to be ~50% fat (i.e., for an animal-based diet; Speth 2010), and brains are roughly 50% fat, then a near-exclusive diet of brains might be predicted. Availability of other foods rich in fats or easily digested carbohydrates would lessen the reliance on brains.

Intestines, especially of ungulates, could also represent an important item of diet partly because semidigested chyme would provide an easily accessed source of energy. Furthermore, they are readily eaten by Hadza (Buck et al. 2016).

In sum, there is no evidence of modern *H. sapiens* populations surviving on raw foods, but possible diets allowing earlier *H. sapiens* to have lived without fire require easily chewed and fat-rich foods, of which brains and guts are the most plausible. But these scenarios are speculative. Despite cooking their main meals, even well-adapted Arctic populations living on high-fat diets suffer extreme food shortages (Balikci 1989; Hardy et al. 2015). It is doubtful that they would survive if they were forced to eat all their food raw.

*Why Does Homo sapiens Find It So Difficult to Thrive on Raw Foods?*

The inferred inability of *H. sapiens* to survive on raw wild diets is explicable by a series of adaptations that have apparently promoted efficiency in processing easily digested foods at the expense of being able to process relatively indigestible foods. The best-known adaptations are the diminution of the human mouth, jaw muscles, jaw, incisors, molars, stomach, cecum, and colon compared with those of nonhuman primates (Martin et al. 1985; Perry et al. 2015; Ungar 2012; Wrangham 2009). Overall, Aiello and Wheeler (1995) estimated that the human gut is 60% of the expected size for a primate. Note that Hladik, Chivers, and Pasquet (1999) presented data to claim that the human gut was the same size as expected in a nonhuman primate of the same body size. However, their data were solely for absorptive mucosa, that is, the small intestine. In humans the small intestine is indeed the size expected by body mass, whereas the big reductions are in the cecum and colon (Martin et al.
1985). These reductions appear to be responsible for humans having a relatively small intake of dry weight of food per day compared with nonhuman primates (Barton 1992) and being relatively poor at digesting long-chain carbohydrates (Milton and Demment 1988). Presumably the reductions could not have evolved until consumers had consistent (year-long) access to appropriately calorie-dense, easily chewed, and easily digested foods.

Numerous parallel adaptations to cooked food can be expected in physiological traits, such as in digestive enzymes. A leading candidate is the amylase system, which has been putatively associated with increased consumption of starch (Perry et al. 2007), specifically cooked starch (Hardy et al. 2015). Compared with chimpanzees and bonobos, humans have been found to have a three or more times increase in copy number of the salivary amylase gene AMY1, which appears responsible for levels of salivary amylase protein being at least three times as high as in Pan (Perry et al. 2007). No increase in salivary amylase copy number compared with Pan was found for Neanderthals or Denisovans (Perry et al. 2015). In theory this could mean that adaptation to cooked diets occurred in the Homo lineage after the splits from Neanderthals and Denisovans. However, only one individual has been characterized for each of the latter species, and it is not known whether duplication of amylase is associated with increased starch consumption (Carpenter et al. 2015). Even if it were, whether the amylase difference between Pan and H. sapiens is associated with cooking or only with an increase in the starch component of the diet is unknown (Perry et al. 2015). More information is therefore needed to make the amylase system informative about the prehistory of cooking.

A different approach to investigating physiological adaptations to cooking uses gene expression. Carmody et al. (2016) found that genes expressed in the livers of mice eating cooked food have been under positive selection in H. sapiens, Neanderthals, and Denisovans. The cooking-related genes were associated with lipid-related metabolic processes on meat diets and with carbohydrate-metabolic processes on tuber diets. While this research has not identified a specific cooking-related phenotype, it suggests that human adaptation to a cooked diet occurred before the evolution of Neanderthals and Denisovans, that is, before 550–765 ka (Prüfer et al. 2014). However, similar cautions apply as to the amylase studies.

The question arises as to why Neanderthals would have had “cooking genes” given evidence that they sometimes lived without using fire (Henry 2017). One possibility is that Neanderthals cooked sufficiently often to maintain their genetic adaptation. Another is that the genes were retained from a cooking-dependent ancestor despite a low frequency of cooking.

What Diet Type Shaped the Digestive Anatomy of Homo erectus?

The evidence of predictable high-energy gain from eating cooked food is helpful because the evolution of H. erectus was marked by an increase in total energy expenditure (e.g., Antón and Snodgrass 2012). Importantly, there is no subsequent time in human evolution when a marked increase in energy use has been suggested. Because cooking is strongly associated with an increase in energy gain, it is therefore predicted to have been adopted by H. erectus (Wrangham 2006). Paleoanthropologists routinely attribute increased energy use by H. erectus to increased reliance on animal-sourced foods (e.g., Zink and Lieberman 2016). However, contemporary evidence indicates that cooking has a much greater effect on energy gain than meat as shown by the robust performance of vegetarians eating cooked food compared with meat-eating raw foodists (see “Adaptation to Cooked Diets”).

Changes in H. erectus anatomy are critical for reconstructing diet. Homo erectus digestive anatomy is known from teeth and jaws and inferred from rib cage and pelvis. Homo erectus incisors and molars were markedly smaller than in Homo habilis, especially the third molar (Ungar 2012). Their jaws were similar in absolute size to H. habilis (Antón and Snodgrass 2012), which means that in relation to body mass, the jaw of H. erectus was relatively small (Wood and Collard 1999; body mass estimates: australopiths 36–44 kg, H. habilis 34 kg, H. erectus 57 kg).

Aiello and Wheeler (1995) proposed that H. erectus also experienced a major reduction in the size of the gut based on a reconstruction by Schmid (1983) of the rib cage of H. erectus as being barrel shaped compared with more bell shaped in australopiths and living great apes: the flared shape is thought to allow a large intestinal capacity below the ribs. In addition, the pelvis was seen as relatively narrow compared with earlier hominins, suggesting a small intestinal floor supporting what was therefore considered to be a relatively small gut compared with previous species. These points supported the idea that H. erectus acquired a small gut at about the same time as getting smaller teeth, mouth, and jaws.

However, subsequent analysis has changed the reconstruction of the H. erectus pelvis because H. sapiens now appears to be the only species of Homo with a reduced pelvis compared with australopiths (Holliday 2012). This means either that the size of the pelvis is less informative about the volume of the gut than Aiello and Wheeler (1995) suggested or that the Homo gut remained large until the evolution of H. sapiens. For the moment I assume the former conclusion, that is, the pelvis is not well correlated with gut size (see “There May Have Been Important Variation in Gut Size within Post-Habiline Homo”).

The idea that these changes to the jaws, teeth, and guts were the result of a dietary improvement is universal, and the leading candidate diet has long been increased animal-sourced foods, especially high-fat meat and marrow. However, the animal-food idea faces a major difficulty. Dietary adaptations must be relevant not only to preferred foods but also to fallback foods, that is, those eaten during periods of food scarcity. Such fallback periods occur frequently, approximately every year, regardless of habitat: they are found even in rainforests for great apes (Marshall and Wrangham 2007) and are well documented for African dry-country hunter-gatherers (Speth 2010).
So the difficulty is to understand what an importantly carnivorous *H. erectus* would have eaten during the inevitable periods when animal products were inadequate. Presumably *H. erectus* incorporated some plant matter in their diets just as recent hunter-gatherers do. But unlike hunter-gatherers, if *H. erectus* did not control fire, they would have had to eat their plants raw. Because neither molars nor guts indicate an ability for *H. erectus* to utilize raw plants high in structural fiber, this makes no sense. Either a solution must be found to this problem or *H. erectus* had to cook. Two noncooking solutions are worth considering.

First, the reduced digestive system could have been made possible by a commitment to fat eating as implied by Ben-Dor, Gopher, and Barkai (2011). As discussed for *H. sapiens*, prey brains would have been one of the few sources of fat in fallback seasons for *H. erectus*. This hypothesis should eventually be testable by the fossil record.

Second, *H. erectus* might have physically processed plants (probably underground or underwater storage organs [USOs]) before consumption in ways that allowed teeth to be functional despite being small and that allowed fermentation to occur without a large colon. Zink et al. (2014) and Zink and Lieberman (2016) proposed this scenario after showing that mechanical tenderization decreased the toughness of tubers by 42%

Against the proposed importance of physical processing, however, mechanical tenderization has limited benefits to judge from the fact that raw foodists suffer energy deficiencies despite using electrical blenders to produce smoothies. Furthermore, no ethnographic or primate models seem to be known of physically processing a food for consumption raw. Contemporary foragers sometimes use techniques such as hammering (to extract an edible seed), but the seed itself is not smashed unless it is going to be cooked. These arguments mean that *H. erectus* was unlikely to have been able to live off raw plant foods even if they were mashed. Accordingly, even if *H. erectus* had an ape-sized gut, the puzzle remains of why teeth, jaws, jaw muscles, and mouth size became reduced.

**Did Homo erectus Have the Cognitive Ability to Cook?**

Warnken and Rosati (2015) have shown that chimpanzees have the cognitive ability to understand the transformative effects of cooking and sufficient inhibition to carry food to a cooker rather than eat it unripe. This indicates that *H. erectus*, with a presumably greater understanding of cause-effect relationships and more inhibitory ability, was plausibly able to cook.

**Use of Honey**

The symbiotic relationship between humans and the greater honeyguide bird (*Indicator indicator*) has been proposed to depend on a long evolutionary history of controlling fire (Crittenden 2011; Marlowe et al. 2014; Wrangham 2011). Honey-guides are genetically adapted to leading humans toward *Apis mellifera* beehives, from which humans extract honeycomb. Humans benefit by finding honey more quickly, while honey-guides benefit by feeding on otherwise unattainable products (Spottiswoode, Begg, and Begg 2016). African hunter-gatherers use smoke to quell the bees’ defensive response, suggesting an ancient control of fire. However, this proposal has been weakened by Kraft and Venkatamaran’s (2015) finding that some populations of honey collectors use plant volatiles rather than smoke to control bees. So collecting *Apis* honey in the Paleolithic might not have depended on controlling fire.

**Problems in Understanding Adaptations of Homo erectus If They Were Limited to Raw Food**

**Scavenging on Raw Food Would Be Difficult Except for Marrow or Brains**

Eating of meat and marrow is evidenced back to 2.5 million years ago (de Heinzelin et al. 1999) and arguably to 3.3 million years ago (McPheron et al. 2010; but see Domínguez-Rodrigo and Alcalá 2016). However, only by 1.8 million years ago do hominin sites indicate regular butchering of large animals (Potts 2012). This suggests that *H. erectus* was the first species to rely extensively on access to animal foods and raises the question of how they escaped a high risk of disease from pathogens (Ragir, Rosenberg, and Tierno 2000). One answer would be a focus on eating marrow, which has a low bacterial load as a result of being protected inside bone (Smith et al. 2015). Brains are probably similarly safe.

Nevertheless, cut marks show that edible meat portions were also commonly removed. Careful attention paid by the butchers to identifying dangerously infected sections of meat would have helped reduce the dangers of eating raw wild meat, but cooking would still have been a safer strategy (Smith et al. 2015).

**Hunting Effort Would Be Mysterious (Time Would Be Constrained If Food Is Raw)**

Although exploitation of meat and marrow can lead to high gains, nowadays those foods are not dependable as a source of calories for tropical hunter-gatherers because the amount of animal food obtained on any given day is often inadequate (Speth 2010). This suggests that the same would have been true in the Lower Paleolithic. Accordingly, individuals who invested in trying to hunt or find carcasses would sometimes fail and would therefore need to have an alternative source of food that day. The problem is easily solved in modern humans: when an entire group runs short of animal products, they are able to eat starchy plant foods that are consumable quickly because they have been cooked. Plant foods are generally less satisfying than animal foods, but their merit is that they are more easily obtained and are, therefore, relatively predictable. However, the value of plant foods depends on their being cooked not only because cooked plants provide more energy than raw plants but also because they can be eaten much faster (perhaps in 10%–20% of the time needed for raw plants; Organ et al. 2011).
Without access to cooked food, failed hunters would need many hours to chew and digest plant foods that would provide their daily energy requirements. This means that a significant increase in the amount of meat eaten, as occurred most clearly with *H. erectus*, depended on having cooked food as a substitute food resource on days when no animal-source foods were obtained (Wrangham 2009).

**Brain Size Increase in Homo erectus Would Be Challenging to Understand**

Aiello and Wheeler (1995) recognized two major rises in human brain size (cf. Rightmire 2004). The first was around 2 million years ago, including *H. habilis/rudolfensis* and *H. ergaster*, which they attributed to increased meat eating. The second was in the latter half of the Middle Pleistocene. They suggested that cooked food could have been an important factor in the second rise.

If the mid-Pleistocene increase in cranial capacity was due to hominin exploitation of cooked food, the fact that cooked food increases energy gain by 30% or more should be recognized in other changes as well. But in the mid-Pleistocene there are no other significant signals of improved dietary quality or any marked decline in tooth size that would be expected to accompany an increasingly tender diet produced by cooking. This makes the idea of cooked food being introduced at that time problematic.

Fonseca-Azevedo and Herculano-Houzel (2012) drew attention to a second difficulty by postulating that the positive influence of cooked food on brain size was not achieved until the mid-Pleistocene (i.e., with *Homo heidelbergensis*). Based on extrapolation from living primates, they calculated the metabolic cost of servicing bodies and brains of hominin species. Noting that a combination of large body and large brain is a difficult challenge because of the high maintenance costs of both, they found that if *H. erectus* ate only raw food, they would be required to chew for as many hours per day as a gorilla, that is, up to 8 hours or more. Their calculation seems to be an underestimate because it assumes that digestive effectiveness was as high in *H. erectus* as in gorillas, which is unlikely given the smaller teeth (and possibly smaller gut) of *H. erectus*. The demand of exceptionally high foraging time (which would necessarily be associated with high resting time to allow digestion to occur) appears to be impossible for a species that supposedly had high travel distances (cf. Organ et al. 2011).

Fonseca-Azevedo and Herculano-Houzel (2012) concluded that *H. erectus* and subsequent species needed to eat cooked food in order to obtain enough calories per day to satisfy the combination of larger bodies and larger brains without spending all day chewing.

The major alternative is that *Homo* (starting presumably with *H. habilis*) fueled their larger brains thanks to a diet that included more raw meat and fat products of animals than before (Leonard, Snodgrass, and Robertson 2007). This is premised on animal foods being more energetically efficient than plant foods. In favor of this explanation, among carnivores a diet richer in vertebrate animals is correlated with increased relative brain size (Swanson et al. 2012). Against it, allometric variation in carnivore brain size is explained principally by between-family differences (Finarelli and Flynn 2009). Within families, the most striking variation in eating vertebrates is found in the Ursidae, from the vegetarian giant panda *Ailuropoda melanoleuca* to the vertebrate-eating polar bear *Ursus maritimus*. If meat products are important for brain growth, polar bears should have relatively large brains. But although larger bear species eat more vertebrates, the slope of brain volume on body mass is the same in bears as in basal Carnivora. So bears have larger brains than other carnivores without any evidence that a diet incorporating more meat influences this relationship (Finarelli and Flynn 2009).

If cooked food explains the rise in brain size in *H. erectus*, what explains the later, mid-Pleistocene grade shift in brain size (Rightmire 2004)? One possibility is that developments in hunting ability led to increased procurement of fat-rich prime adults compared with weakened, fat-depleted prey (Stiner, Bakkai, and Gopher 2009). The interesting problem that remains is how sufficient dietary fat could be maintained during seasons of food scarcity.

**Running Would Not Be Favored without the Use of Fire**

Endurance running is a unique human ability compared with other primates. Bramble and Lieberman (2004) argue that it is made possible by various anatomical adaptations in *H. sapiens* that occur also in *H. erectus* but not earlier, including features that promote stabilization of head and trunk and energy storage and shock absorption in the foot. Their proposals have been criticized on the basis that australopithecines may have had the same adaptations, allowing them to be equally effective endurance runners (Pontzer 2012).

Physiological adaptations for endurance running include increased ability to lose heat compared with apes, such as longer legs in relation to body mass (Pontzer 2012). Loss of body hair would make a particularly important contribution to the ability to lose heat. In support of an early loss of body hair (and the associated evolution of pubic hair), the human pubic louse (*Pthirus pubis*) diverged an estimated 1.84–5.61 Ma from its closest living relative, the gorilla louse (*Pthirus gorillae*; Reed et al. 2007). However, a critical function of body hair is to retain heat during sleep, which means that sufficient reduction of body hair to allow endurance running would seem to depend on a system of heat maintenance during sleep other than an insulating layer of hair.

Clothes are one possibility, but parasite evidence indicates clothes were adopted relatively late. Thus, clothing appears to have been responsible for a functional split between head lice and body lice (both *Pediculus humanus*), which are estimated to have been genetically separated since 83–170 ka (Perry 2014), long after the evidence for endurance running.
Other than clothing, the obvious way for a species with reduced body hair to keep warm at night is to use fire (Wrangham 2009). This suggests that endurance running could not have occurred without the loss of body hair made possible by the control of fire.

In sum, endurance running presumably depended on the loss of an insulating layer of hair and, therefore, on non-insulated humans being able to warm themselves at night by a fire. The evidence for Lower Paleolithic endurance running therefore suggests that fire was controlled by then.

Sleeping on the Ground Would Not Be Favored without the Use of Fire

The adaptations of *H. erectus* to terrestrial locomotion include reduced climbing ability. Having an essentially modern frame with long legs, *H. erectus* cannot be expected to have been able to climb into trees every night to make a bed of leaves and twigs in the way that most great apes do. They therefore presumably slept on the ground (Coolidge and Wynn 2006). Gorillas regularly sleep on the ground, as do chimpanzees in some populations, but only where predators are not a serious risk (Koops et al. 2007). Terrestrial sleeping for humans in a predator-rich savanna, by contrast, can be expected to be very dangerous. Even today people in lion-rich environments are most vulnerable to predation shortly after dark (Packer et al. 2011). Accordingly, the reduction of climbing adaptations that occurred with *H. erectus* appears to signal the simultaneous evolution of a method of achieving safety at night. Control of fire is the obvious possibility because it is the principal method used by modern humans sleeping in the kinds of habitats occupied by *H. erectus* (Wrangham and Carmody 2010).

Shipman (2009) objected to this proposal by noting that antelope sleep on the ground without fire. However, antelope sleep less than humans (Richard Estes, personal communication). Smaller species tend to hide at night, under bushes, for example. Larger species avoid cover and prefer to be in the open. Although no details are known about sleeping patterns of African ungulates, they certainly do not have long periods of relaxed sleep. Even domesticated ungulates sleep briefly; according to Elgar et al. (1988, 1990), total sleep time per 24 hours is less for artiodactyls (mean 5.3 h) and perissodactyls (4.8 h) than in 10 other orders of mammals, including primates (10.3 h).

In relation to body mass, domesticated ungulates also have the shortest cycle of REM sleep and slow-wave sleep of nine orders of mammals, whereas primates have the longest. Short REM cycles in ungulates fit with the observation by Richard Estes (personal communication) that wildebeest (*Connochaetes taurinus*) sleep deeply for only a few minutes at a time. In general, species in riskier environments have less REM sleep (Lesku et al. 2006).

Thus, ungulates sleep little compared with humans, enabling them to be relatively vigilant, and they sprint faster. Yet their mortality from predation is clearly much higher than in humans. Among Kalahari foragers, data collected by Polly Wiessner indicated that predation risk on humans is sharply higher when sleeping without fire than when fire is present (Wrangham and Carmody 2010).

In short, the pattern of sleep by large herbivores is not an argument against the claim that *H. erectus* would have been very vulnerable if they slept on the ground unprotected by fire or some alternative system. The proposal that *H. erectus* did not control fire, therefore, demands a novel explanation of their defenses at night, such as the evolution of an ungulate-like pattern of sleep, a surprisingly good ability to sprint, or the building of effective fences.

Problems for the Cooking Hypothesis

Why Were Population Densities So Low?

Cooking presumably increased both the range of foods that could be eaten and the total energy gained from those foods. Yet although *Homo* achieved a wide geographical distribution around the time of *H. erectus*, it appears to have been a relatively unsuccessful genus in terms of its population densities and total numbers, at least intermittently. Later, Neanderthals were in small, widely dispersed groups, and *H. sapiens* experienced a severe bottleneck around 70,000 years ago. How do we reconcile the benefits of cooked food with the poor ecological success of *Homo* before agriculture?

One possibility is that by adapting to forego the ability to eat fiber-rich foods (such as raw leaves, stems, and USOs), *Homo* boxed themselves into requiring even higher-quality foods than before. Such foods would be animal products and low-toxin, low-lignin plants containing high concentrations of sugar or starch. The acquisition of adaptations to take maximal advantage of cooked foods may thus have been a Faustian pact in which the benefit of high-quality foods was set against the loss of ability to digest foods on which other hominoids (such as chimpanzees and orangutans) can readily survive.

Why Was *Homo habilis* Intermediate?

There is increasing evidence that the evolution of *H. erectus* was not a single “Adamic” event (Hublin 2015) but a “fuzzy transition” occurring in a complex series of shifts (Antón, Potts, and Aiello 2014; Antón and Snodgrass 2012). This means that whatever the dietary change responsible for *H. erectus*, its effect took time to be felt, and geographical variation suggests that the process happened erratically in space. Thus, the conclusion that *H. erectus* was the first obligatory cook leads to the expectation that species before *H. erectus* would not show indications of being adapted to cooked food. In line with this prediction, *H. habilis* has a similar postcanine crown size to *Australopithecus africans* and a similarly robust jaw in relation to body mass (Eng et al. 2013; Wood and Collard 1999).

However, there are at least two problems that the cooking hypothesis must deal with. First, based on one specimen (OH13),
Eng et al. (2013) modeled *H. habilis* as producing only a low maximum bite force in line with later *Homo* and different from the higher bite forces of *Australopithecus* (and contemporary great apes). This result came from *H. habilis* having a relatively small second molar. Eng et al. (2013) therefore suggested that *H. habilis* might be adapted to foods that had been mechanically processed to reduce their toughness or other physical challenges. In support, dental microwear studies indicate that *Australopithecus* ate tougher foods than *H. habilis* (Ungar and Scott 2009; Villmoare et al. 2015). Thus, a potential solution to *H. habilis* having a craniofacial structure that is to some extent intermediate between *Australopithecus* and subsequent *Homo* is that a period of mechanical processing preceded cooking. While this makes sense given that stone tools that could cut and pound food were available long before *Homo erectus*, it also raises the possibility that the reduced craniofacial robusticity of *H. erectus* reflects a continuation of the same process (Zink and Lieberman 2016). According to this idea, mechanical, nonthermal processing became even more important and effective in *H. erectus* than in *H. habilis* and accounts for the small teeth (a reduction of ca. 25% in size), shorter face, and more lightly built jaw.

The second challenge has a similar implication of being able to explain *H. erectus* biology on the basis of adaptations begun in *H. habilis*. Before “Homo-ization” of the jaw and teeth, brain size in *H. habilis* had risen from the australopithecine level of 385–571 cc to 510–750 cc (Antón, Potts, and Aiello 2014; Spoor et al. 2015). Whether this was due to increased animal foods in the diet, nonthermal processing, or some other change, the increase in diet quality that is indicated by the rising brain size in *H. habilis* could have been continued and caused the changes seen in *H. erectus*.

A solution offered by the cooking hypothesis is that before the obligatory adaptation to cooking indicated for *H. erectus*, *H. habilis* used fire intermittently. As a result, they were able to regularly eat relatively tender food (as indicated by microwear; Ungar 2012) and gain sufficient extra energy to promote an increase in brain size. However, because they could not guarantee having access to cooked food, they retained dental and digestive adaptations that allowed them to effectively chew plant foods when animal foods were scarce.

Despite these problems for the idea of a single shift encompassing diverse features of *Homo* simultaneously, it is often concluded that habilines had a faster life history than *H. erectus* (e.g., “non-erectus early Homo was smaller and developed more quickly than *H. erectus*”; Antón and Snodgrass 2012:S487). A slower life history could imply earlier weaning and more dependence of juveniles on adults for food (Thompson and Nelson 2011). Early weaning is clearly hard to reconcile with a raw diet unless it predictably included such elusive foods as brain and fat-rich marrow. Unfortunately, although these arguments are intriguing, they are premature given that it remains unclear how different the life history of *H. erectus* was from its antecedents (Schwartz 2012).
body, and larger brain have omitted any consideration of the cooking hypothesis (Antón and Snodgrass 2012; Potts 2012).

In fact, however, the evidence of increased dietary quality in the early Lower Paleolithic is only one of several sources of support for the cooking hypothesis, as discussed above. Furthermore, the emergence of Homo erectus is not adequately accounted for by an increased frequency of meat eating. Thus, while the cooking hypothesis may be wrong, it cannot fairly be dismissed by ignoring it.

Accordingly, two questions must be answered before the time for the control of fire is assigned to the mid-Pleistocene. First, how could Homo erectus use increased energy, reduce its chewing efficiency, and sleep safely on the ground without fire? Second, how could a cooked diet have been introduced to a raw-foodist, mid-Pleistocene Homo without having major effects on its evolutionary biology? Satisfactory answers to these questions will do much to resolve the tension between archaeological and biological evidence.

The results should be rewarding. The control of fire and the emergence of cooking had numerous effects on human biology and behavior, including cognition and cooperation (Attwell, Kovarovic, and Kendal 2015; Burton 2009; Dunbar and Gowlett 2014; Gintis, van Schaik, and Boehm 2015; Wiessner 2014; Burton 2009; Dunbar and Gowlett 2014; Gintis, van Schaik, and Boehm 2015; Wiessner 2014; Burton 2009). A better understanding of when the process started will have wide-ranging implications for human biological and social evolution.

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Fire for a Reason

Barbecue at Middle Pleistocene Qesem Cave, Israel

by Ran Barkai, Jordi Rosell, Ruth Blasco, and Avi Gopher

Qesem Cave is a Middle Pleistocene site in Israel occupied between 420 and 200 ka. Excavations have revealed a wealth of innovative behaviors most likely practiced by a new hominin lineage. These include early evidence for the habitual and continuous use of fire, the repeated use of a central hearth, systematic flint and bone recycling, early blade production technologies, social hunting strategies and meat-sharing practices, and more. Fire was used throughout the 200,000 years of human occupation of the cave primarily for meat roasting and cooking. Roasting and cooking, we argue, had an important role in providing the necessary caloric intake of the cave’s inhabitants. We see fire as an essential element of the new post-Acheulian human adaptation in the Levant. The ample recurring evidence for focused and repeated use of fire for dietary purposes suggests that fire production, control, use, and maintenance were habitually practiced by the cave’s inhabitants and that fire-induced calories became central for their survival. We present an integrative view regarding the use of fire at Qesem Cave and discuss the role of fire within the framework of the significant cultural and biological transformations that took shape in the post-Acheulian Levant during the Middle Pleistocene.

Introduction

The use of fire at Middle Pleistocene Qesem Cave (Qesem) has been discussed, and the repeated use of a central hearth at 300 ka has been demonstrated in previous publications (Falguères et al. 2015; Karakanas et al. 2007; Shahack-Gross et al. 2014). In this paper, our aim is to view the human use of fire at Qesem in the context of cultural and biological transformations that took shape in the Levant at ca. 400 ka and to specify the major uses of fire at Qesem in particular and in the late Lower Paleolithic period in the Levant in general. We claim that the common and continuous use of fire for roasting meat at 400 ka at Qesem was a Rubicon crossed for the first time, and it characterizes human existence from that time to this very day. We contend that the combination of specific circumstances during the late Lower Paleolithic period in the Levant triggered human communities to make use of their extensive cultural and social capabilities as well as their profound familiarity with their environments and their survival skills by using a new mode of adaptation. The use of fire for roasting meat and for cooking in general was a central element of this new adaptation, and the evidence from Qesem is consistent with this hypothesis. We start with a general introduction about the Acheulo-Yabrudian Cultural Complex (AYCC) as reflected by the plethora of information gathered from the archaeological deposits of Qesem. Then we focus on direct and indirect evidence for the use of fire at the cave (ash, hearths, burned bones and lithics, stone tools used in butchering, and charcoal contained in dental calculus). Finally, we present our hypothesis regarding the earliest, continuous, and common use of fire for roasting meat and cooking and its implications to human diet, culture, and adaptation.

The Acheulo-Yabrudian Cultural Complex and the State of the Art of Qesem Cave Studies

The AYCC is a Middle Pleistocene, late Lower Paleolithic cultural entity of the Levant. The AYCC consists of three distinct lithic industries: the Acheulo-Yabrudian (a flake industry with a notable presence of handaxes), the Yabrudian (a flake industry dominated by Quina and demi-Quina scrapers), and the Amudian (a blade-dominated industry; see Bar-Yosef 1994; Copeland 2000; Rust 1950). Stratigraphically, the AYCC repeatedly postdates the Lower Paleolithic Acheulian and predates the Middle Paleolithic Mousterian. The absolute chronology of the AYCC covers a range of over 200 kyr between ca. 420 and

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200 ka (Barkai et al. 2003; Gopher et al. 2010). New thermoluminescence and electron spin resonance dates from Qesem and Misliya Caves accord well with this range (Falguères et al. 2015; Mercier et al. 2013; Valladas et al. 2013). AYCC sites are known from the central and southern Levant in both caves and open air settings but mostly in caves or rock shelters.

Blade production in the Amudian industry is of special interest and is one of the major innovations of the AYCC (e.g., Bar-Yosef and Kuhn 1999). Middle Pleistocene blade production is a unique “ahead of its time” technological innovation that is part of a set of cultural and behavioral transformations that took shape in the Levant at ca. 400 ka and that should be viewed as a local innovation that persisted for 200 kyr. The Amudian industry is characterized by the systematic production of blades and tools made of blades. Alongside blade production, a significant flake component also appears, including side scrapers in various frequencies (Copeland 2000; Jelinek 1982, 1990). Qesem has shown that the Amudian represents a major industry of the AYCC, equivalent in scale to the other known industries (e.g., Gopher et al. 2005; Shimelmitz, Gopher, and Barkai 2011, 2015).

In the Yabrudian industry, the innovative appearance of the Quina chaîne opératoire for the shaping of Quina scrapers (see Bourguignon 2001) is of note. These distinctive scrapers are well known from Middle Paleolithic Mousterian of Europe. However, the Yabrudian is much older than the European manifestations of the Quina phenomenon. In the Levant, Quina scrapers appear in large numbers in the AYCC Yabrudian (by the thousands at Qesem and Tabun caves) but cease to appear in post-AYCC Middle Paleolithic Mousterian sites. The fact that Quina scrapers are not known from earlier Acheulian contexts makes their presence in the Yabrudian unique and quite enigmatic.

As for the makers of the AYCC, this remains an open question. The Galilee Man skull from Zuttiyyah Cave (Freidline et al. 2012; Keith 1927; Zeitoun 2001) and the dental remains from Qesem hint at a new, post-Acheulian, post-erectus hominin lineage in the Levant at ca. 400 ka (Ben Dor et al. 2011; Hershkovitz et al. 2011). This statement is supported by new studies of Middle Pleistocene skeletal remains, mainly dental remains from the Levant and beyond (Le Cabec et al. 2013; Liu et al. 2013; Rink et al. 2013), as well as genetic evidence suggesting a Middle Pleistocene (before 300 ka) date for the ancestors of modern humans and/or Neanderthals (e.g., Endicott, Ho, and Stringer 2010; Mendez et al. 2013).

As for the use of fire, the evidence indicates that human use of fire during the AYCC in the Levant was common and relatively widespread (see a recent review in Shimelmitz et al. 2014). Earlier use of fire in the Levant was reported at Gesher Benot Ya’aqov only (Alperson-Afil 2017; Alperson-Afil and Goren-Inbar 2010; Goren-Inbar et al. 2004). Such “early fire” occurrences (Gowlett 2010), or the early interactions between humans and fire, are evident during the Early and Middle Pleistocene in Africa and Asia (e.g., Berna et al. 2012; Chazan 2017; Gao et al. 2017; Gowlett et al. 2017; Hlbik et al. 2017). The turning point from “early fire” to the habitual use of fire is a matter of dispute. Roebroeks and Villa (2011) describe habitual use of fire as a systematically repeated use of fire in specific sites and/or regions. Based on an increased number of archaeological sites associated with evidence for fire being extensively used in domestic contexts, they suggested that the earliest habitual use of fire occurred in Middle Pleistocene (ca. 400–300 ka) Europe and southwest Asia. On top of that, the probable use of fire in the Acheulian was never demonstrated. We argue that starting at ca. 400 ka, hearths were used, first and foremost, for roasting meat, and as a result, burned bones are found in abundance in post-Acheulian sites (Fernández et al. 2012; Karkanas et al. 2007). Thus we concur with the statement that during the Lower Paleolithic, Acheulian meat was most probably consumed raw (Bar-Yosef 2006). As for the AYCC, the evidence from Qesem presented below indicates an unequivocal change regarding the presence and use of fire in archaeological sites from this point in time onward.

Qesem Cave

Qesem is located on the western slopes of the Samarian hills some 12 km east of the Mediterranean at 90 m asl. With nearby large springs and being located at the ecotone between the swampy basins of the coastal plain to the west and the mountainous ridges of Samaria, this location provides a rich Mediterranean biome. To date, the excavation exposed some 70 m² (130 m³) using 50 × 50 cm spatial units, full recovery through a 2.4 mm net, and screen washing through 0.5–0.8 mm for microfauna-bearing layers.

Qesem is a sediment-filled karstic chamber that became available to humans following slope erosion (Frumkin et al. 2009). The stratigraphic sequence was divided into two major parts: the lower consists of a >6.5 m accumulation of sediments with clastic content, gravel, and clays, and the upper consists of 4.5 m of cemented sediment with a large ash component. The lower part was deposited in a closed karstic chamber, while the upper part was deposited when the cave was more open, as indicated by the presence of calcified rootlets (Karkanas et al. 2007).

Qesem is a Middle Pleistocene (MIS 11-7) site dated by various methods (over 100 dates) to between 420 and 200 ka (Barkai et al. 2003; Falguères et al. 2016; Gopher et al. 2010; Mercier et al. 2013). The whole stratigraphic sequence is assigned to the AYCC (Barkai and Gopher 2011, 2013).

Ongoing research at the site provides ample evidence of innovative behaviors. This pertains, for example, to serial blade production (Shimelmitz, Gopher, and Barkai 2011), the acquisition of raw material for selected tool types from underground sources (Verri et al. 2004), the production of Quina scrapers using Quina debitage and retouch technologies (Lemorini et al. 2016), intensive and varied recycling of flint and bone (Parush, Gopher, and Barkai 2016; Rosell et al. 2015), group hunting of prime-aged animals (mainly fallow deer; Blasco et al. 2014, 2016a), specialized butchering techniques and unique meat-sharing habits (Stiner et al. 2009, 2011), intensive use of bone
retouchers, the habitual use of fire, hearth-centered and spatially patterned activities, and more—all well established at Qesem and present throughout the cave’s sequence. Qesem contains two of the three AYCC industries: the blade-dominated Amudian and the scraper-dominated Yabrudian. Viewing these two as separate entities is at present challenged by data indicating their coexistence at Qesem. Below we will present a summary of the data on the lithics and human remains. The fauna will be presented separately because it directly relates to understanding the use of fire at the cave.

The Lithic Assemblage

While Amudian-bearing levels are dominant throughout the cave’s stratigraphic sequence, the Yabrudian is less conspicuous and is stratigraphically and spatially restricted. Raw-material studies were oriented to both characterizing flint types used and locating their sources in the landscape. Preliminary results show the use of a large variety of flint types (over 80), some of which were selected for specific types of tools or technological requirements. A concentration of over 10 geological sources yielding flint types used at the cave was found within 5 km of the site. Several sources are, however, located some 15 km away from the site (Wilson et al. 2016). Earlier raw-material studies provided evidence for flint procurement by both surface collection and quarrying from specific, designated primary subsurface sources (Verri et al. 2004, 2005). Quarried flint was directed toward the production of specific tool types (Boaretto et al. 2009). It is of note that the AYCC of Tabun cave has items made of flint quarried from deep sources as well (Verri et al. 2005).

The Amudian blade industries provide very large samples. Blade production at Qesem shows a full chaîne opératoire, including well-selected flat flint nodules, core shaping, and blade production, use, and discard. Amudian blades were mostly used for cutting, butchering, and defleshing activities of soft tissues and for a short time (Wilson et al. 2016). Moreover, homogeneity in blade production technology and in blade characteristics was discerned throughout the Levant, reflecting a shared AYCC template regarding the properties of the target blades (Shimelmitz, Barkai, and Gopher 2016). Amudian blade production reflects a systematic, intensive, thoughtful, and straightforward technology—a conscious technological choice of skilled flint knappers constantly used for over 200 kyr (Shimelmitz, Barkai, and Gopher 2016; Shimelmitz, Gopher, and Barkai 2011). Early blade industries were reported from Africa as well (Johnson and McBrearty 2010; Wilkins and Chazan 2012). The interrelations between these industries and the Amudian is intriguing in light of a multiple origins (convergent) hypothesis for early Middle Pleistocene blade technology (Barkai and Gopher 2013; Wilkins and Chazan 2012).

Recycling flint is a clear component of both Amudian and Yabrudian assemblages at Qesem and in the AYCC as a whole (e.g., Shimelmitz 2015). Detailed studies of recycled items and recycling products indicate technologically well-established trajectories for the production of designated types of specific sharp flakes and blades (Assaf et al. 2015; Barkai, Lemorini, and Gopher 2010; Parush et al. 2015; Parush, Gopher, and Barkai 2016) for targeted purposes (Lemorini et al. 2015). The scale of recycling may reach almost 10% of the debitage at Qesem (the highest densities may reach 180 recycled items per 1 m3; see Gopher et al. 2016), and if recycled patinated items are added, the frequency rises significantly. Recycling is a well-established behavioral feature characterizing the AYCC (as well as earlier Acheulian technologies; see Agam, Marder, and Barkai 2015; Barkai and Gopher 2013; Shimelmitz 2015) and is most probably oriented toward the intensification of cutting activities.

As for tool typology, an “Upper Paleolithic” tool group made on blades is conspicuous (Gopher et al. 2005). Large, wide, and thick blades were selected for tool shaping, and laminar-shaped items are dominated by a variety of retouched and backed items with few end scrapers. Yabrudian assemblages show an abundance of Quina and demi-Quina scrapers making up to 50% of the shaped items, while blades are less abundant.

A small group (n = 16) of shaped stone balls (spheroids/polyhedrons) was found concentrated in specific stratigraphic and spatial Amudian contexts (Barkai and Gopher 2016). Whether these were used for specific activities in specific contexts it is too early to say. Biface production continued in the AYCC and was quite conspicuous in the Acheulo-Yabrudian at Tabun. Although bifaces are indeed marginal at Qesem and appear as single items in both Amudian and Yabrudian assemblages (Barkai and Gopher 2013), they seem to have been given special attention. Bifaces appear in different stages—including rough-outs. One of the outstanding roughouts is quite large (22 cm long, 15 cm wide, 10 cm thick, and 3,285 g; see Barkai et al. 2013).

Archaeological evidence for knowledge transmission is difficult to attain. We have suggested a change in knowledge-transmission mechanisms between the Acheulian and the AYCC in the Levant in relation to new adaptive strategies and innovations in the lithic sphere, to hunting techniques and butchering practices, to the habitual use of fire (firewood collection, making and maintaining fire), and especially to meat (and maybe other foods) roasting and cooking (Barkai and Gopher 2013). These new AYCC behaviors necessitated knowledge-transmission mechanisms differing to a degree from those practiced in the Acheulian and supported by a new social milieu based on a possible new sociocultural discourse (see Assaf, Barkai, and Gopher 2016; Barkai and Gopher 2013; Ben-Dor et al. 2011). A study of lithic knowledge transmission carried out at Qesem recently relates to the technotypological characteristics of a lithic assemblage from the southern parts of the cave (earlier than 300 ka). The study of knapping trajectories demonstrated distinct features in this assemblage when compared with lithic assemblages from other areas of the cave. These features reflect various levels of knapping skills most probably characterizing both skilled knappers and knappers in the process of learning. This may permit a preliminary assessment of knowledge transmission relating to flint knapping that has taken
place in a designated area (Assaf, Barkai, and Gopher 2016; Assaf et al. 2015).

**Human Remains**

To date, Qesem has yielded dental human remains only; 13 teeth in total from different parts of the stratigraphic column. These included deciduous and permanent teeth of a number of individuals, many of whom were under the age of 20. The basic morphometric study indicates that the Qesem teeth are clearly not of *Homo erectus* (sensu lato). It has highlighted that while some of the traits are more Neanderthal-like, they are generally similar to the Late Pleistocene local populations of Skhul and Qafzeh caves dated to ca. 100 ka. (Hershkovitz et al. 2011, 2016). A 3-D scan of some of the teeth and various subsequent analyses resulted in similar conclusions, although Neanderthal affinities were more emphasized in some of these teeth (Fornai et al. 2016; Weber et al. 2016). While it is quite conceivable that the Acheulian Cultural Complex of the Levant was created by *H. erectus* (sensu lato; see Barkai and Gopher 2013 for details), the dental evidence from Qesem, augmented by the AYCC skull from Zuttiyeh Cave, indicates a new, post-Acheulian, post-*erectus* hominin lineage starting at ca. 400 ka.

We thus see merit in our previous suggestions that the Qesem finds and the AYCC as a whole were produced by a new local human lineage. Obviously the question of why a biological change occurred in the Levant around 400 ka is of major interest. Based on a bioenergetic model conjoined with the cultural transformations demonstrated at Qesem, we offer an explanation accounting for the demise of *H. erectus* and the appearance of a new, locally evolved, post-*erectus* human lineage in the Levant around 400 ka (Ben-Dor et al. 2011). The model suggests that the disappearance of elephants from the human diet in the Levant around this time triggered a selection process in favor of those who were better adapted to hunting larger numbers of smaller, faster animals with high fat content—that is, those who were lighter and more agile. The ingredients of this model include well-known data such as the fact that the elephant is a unique and ideal food package exploited by Lower Paleolithic groups in the Levant for hundreds of thousands of years. It is of note that no elephants are found in Levantine post-Acheulian sites, which suggests this significant part of Acheulian life and diet had ceased in post-Acheulian times. Why elephants disappeared from the human diet in post-Acheulian times in the Levant remains an open question at the moment. However, the fact that elephants are absent from all sites after the Lower Paleolithic implies that rather than a culturally based avoidance or taboo, the most plausible explanation is that elephants were, for some reason, no longer available. Additionally, modern humans have known and generally accepted ceilings on protein and vegetal food consumption, and fat is thus a compulsory component in the human diet for sufficient Daily Energy Expenditure (elephants are a notable package of fat; see details in Ben-Dor et al. 2011). The habitual use of fire for roasting and the new lithic technologies may be listed here as two of the important new cultural elements related to this transformative biological and socioeconomic landscape.

Qesem provides ample evidence on the environment, on human behavioral and cultural adaptation, and on the biology of the hominins that inhabited it. Sealed by sediment accumulation at ca. 200 ka, shortly after desertion, and exposed only 15 years ago, Qesem preserves an outstanding potential not only for studying the communities that inhabited it but also for understanding the AYCC as a whole and its place within the sequence between two relatively intensively studied entities—the Lower Paleolithic Acheulian and the Middle Paleolithic Mousterian. While these two may be regarded as pan-Eurasian phenomena, the AYCC is a local and distinct entity. Although many of the AYCC lithic innovations do not continue into the Mousterian and are replaced by Levallois-dominated industries, some of the most significant cultural and behavioral innovative patterns of the AYCC do continue into later periods (e.g., the habitual use of fire, hunting focused mainly on large and medium-sized ungulates, meat roasting, and more). The AYCC, mainly in its early stage, demonstrates a revolution, so to speak, reflecting a society open to innovative elements. New lithic technologies appeared and were maintained for a period of 200 kyr. Known concepts such as flint recycling have been modified, changed, and intensified. We view the emergence of AYCC blade and Quina technologies in the Levant as an original innovative behavior. The “African connection” of the Qesem assemblages (lithic and faunal) is practically nonexistent, and it has no African counterparts. We suggest that systematic blade production and Quina-scraper production are local innovations aimed at manipulating medium-sized game. A study of Mousterian Quina scrapers from France (Claud et al. 2012) shows their use as butchering tools, and preliminary functional observations on the Qesem scrapers show similar results, although hide working and bone working were observed as well (Lemorini et al. 2016; Zupancich et al. 2016a, 2016b). Amudian blades and Yabrudian scrapers, augmented by a variety of recycling products, may thus be viewed as components of a new meat-cutting set that was developed in the Levant around 400 ka, replacing the long-lived Acheulian meat-cutting tool kit based on flakes and handaxes. This may have accompanied new hunting and meat-sharing practices following the loss of calories previously obtained from elephants. This particular combination of blades and Quina scrapers (as well as recycled products) reflects a specific adaptation that has no counterparts in Africa or Europe.

**Fire Use at Qesem**

The use of fire is apparent throughout the sequence at Qesem, both directly by the large amounts of wood ash and the presence of hearths (Karkanas et al. 2007; Shahack-Gross et al. 2014) and indirectly by the large amounts of burnt flint and burned bones, the organization of activities around the hearth, and the presence of charcoal fragments in human dental cal-
culus. Thus, it is our contention that fire was used habitually, commonly, and repeatedly as early as 400 ka, and one of its most important functions was most likely cooking (see Speth 2012). This section presents this evidence in some detail.

**Direct Evidence for Fire Use**

The direct evidence from Qesem clearly indicates extensive, repeated use of fire between 420 and 200 ka. Micromorphological and isotopic evidence indicates recrystallization of wood ash. Large quantities of burnt bone, characterized by a combination of microscopic and macroscopic criteria, and moderately heated soil lumps are closely associated with the wood ash remains (Karakanas et al. 2007). All the ash structures are related to wood burning and complete combustion. Calcined bones are relatively common as identified, both mineralogically (using the Fourier Transform Infrared Spectrometry [FTIR]) and microscopically, by changes in color, birefringence, chemical alteration, and interference colors. Such a mineralogical transformation occurs at either a very high temperature for a short duration (above 650°C) or from prolonged combustion at temperatures as low as 500°C. This temperature range is commonly reached in campfires, and in the case of Qesem, calcined bones are mainly found in the area where the fireplace is located (see below).

A major component of the Qesem deposits consists of recrystallized wood ashes. The upper ca. 4.5 m of the sequence consist mainly of anthropogenic sediments characterized by completely combusted, mostly reworked wood ashes associated with large amounts of burnt bone, lithic artifacts, and moderately heated soil lumps. The strong cementation of the deposits is explained by calcite that precipitated from dripping waters and the recrystallization of the ash. The isotopic analysis supports the presence of both preserved and recrystallized wood ash in the sediments (Karakanas et al. 2007).

A central hearth was identified during fieldwork and confirmed later by mineralogical and microscopic criteria. Micromorphological evidence shows two superimposed use cycles each composed of shorter episodes, possibly the earliest superimposed hearth securely identified to date (Shahack-Gross et al. 2014). The hearth covers ca. 4 m², making it a uniquely large hearth in comparison with any contemporaneous hearth identified thus far. The hearth is located in the center of the cave and is associated with butchered animal remains and a dense flint assemblage. The central location of the hearth within the cave and the activities associated with it may reflect a pattern of the organization of space by the cave inhabitants. An array of independent lines of evidence was used to analyze this large, central, repeatedly used combustion feature. The evidence for this feature being a hearth is primarily the two microlaminated gray-white layers composed of in situ wood ash that includes charred and calcined bones, microcharcoal, burnt flint, and burnt microscopic clay aggregates. The micro-FTIR data indicate a temperature range that exceeded 500°C (Shahack-Gross et al. 2014). This central hearth—having a uniquely large size, being superimposed, and bearing dense faunal and lithic remains as well as evidence for spatial differentiation of activities around it—provides a glance into fire-related behavior of Middle Pleistocene humans. The sedimentary sequence post-dating this hearth at Qesem is characterized by a high content of ash. It is clear that the Qesem hominins possessed fire in the sense of a maintainable technology. They built campfires inside the cave, and a variety of activities were conducted in the vicinity of these fireplaces. The ash-rich contents of the upper strata as well as the abundant burned remains in the lower strata indicate many fire-building events, supporting the interpretation of habitual use of fire in the cave.

**The Faunal Assemblage**

The Qesem faunal record is extremely rich in all of the layers and is dominated by fallow deer but includes red deer, horse, aurochs, wild pig, and wild ass. Although rare, small ungulates such as goat and roe deer and small prey such as birds are also present (Blasco et al. 2014, 2016a; Sánchez-Marco et al. 2016; Stiner, Gopher, and Barkai 2009 2011). Among the small prey, tortoises show a slightly higher level of representation (Blasco et al. 2016b). The faunal assemblages are characterized by an extremely rare presence of carnivores (Blasco et al. 2014, 2016a; Stiner, Gopher, and Barkai 2009, 2011). A significant amount of anthropogenic bone damage has been detected throughout the stratigraphic sequence, including its earliest levels. The taphonomic characteristics of faunal remains indicate that all assemblages were generated solely by humans occupying the cave and were primarily damaged by their food-processing activities. The ungulate mortality profile is dominated by adult-aged individuals, and in the case of fallow deer, the relative abundance of infantile and young individuals suggests the development of seasonal hunting episodes (Blasco et al. 2014, 2016a; Stiner, Gopher, and Barkai 2009, 2011).

Different types of butchery cut marks have been identified in the form of incisions, sawing marks, scraping marks, and chop marks (ratios between <2% and 12% according to Blasco et al. 2014, 2016a, and Stiner, Gopher, and Barkai 2009). The ungulate specimens show cut marks distributed over most of the skeletal elements, especially on limb bones (fig. 1). The locations of the cut marks indicate that both long-bone epiphyses and shaft fragments bear cuts, although there is a clear predominance of damage on limb-shaft fragments. Tortoise bones from the earliest levels show a relatively high rate of cut marks (13.2%) on the shell and limbs (Blasco et al. 2016b).

The faunal assemblage also includes damage caused during bone breakage to access marrow (fig. 2). The studied samples have preserved diagnostic elements of intentional bone breakage of both long and flat bones, although, as in the case of cut marks, the limb shafts show the highest proportions of damage. The bone surface modification resulting from the anthropogenic breakage includes percussion pits, notches, impact flakes (cortical flakes and scars included), counterblows, and peeling.
Nine bone fragments from the hearth unit and 15 from earlier levels show percussion marks related to the shaping of stone tools. All of these items correspond to the long-bone shafts of small, medium, and large animals, showing damage typically caused by the use of bone as a retoucher (Blasco et al. 2013a; Rosell et al. 2015).

Burning damage affects more than 30% of the bone fragments in all assemblages, including the earliest ones (figs. 1, 3).
Figure 2. Experimental marrow removal through hammer-stone percussion (top) and fossil examples of damage generated during bone breakage to extract marrow in form of percussion notches on limb bones from the hearth assemblage (A), area around the hearth (B), and area under the shelf (C) at Qesem Cave (bottom). A color version of this figure is available online.
In the case of the central hearth, this figure rises to 63.95% of the specimens (Blasco et al. 2014). For the study of this specific modification, macroscopic criteria based on color changes have been used. According to several authors, two main variables seem to influence coloration, namely, the heat intensity and the exposure time (e.g., Brain 1981; Buikstra and Swegle 1989; Gilchrist and Mytum 1986; Johnson 1989; Mayne 1997; Nicholson 1993; Shahack-Gross, Bar-Yosef and Weiner 1997; Shipman, Foster, and Schoeninger 1989; Spennemann and Colley 1989; Stiner et al. 1995). The different responses of the organic and inorganic components of the bones to the rise in temperature lead to color changes and different chromatic stages (mainly brown, black, gray, and white; e.g., David 1990; Grayson et al. 1988; Lyman 1994). For Qesem, the degree of alteration due to burning has been classified into six categories of intensity according to the bones’ color, structure, and homogeneity, with degree 0 representing unburned and degree 5 representing calcined bones. “Sandwich” coloration has also been detected at Qesem, characterized by different coloration in the intracortical tissue with respect to that observed on the outer sides. This occurs when the skeletal element is subjected to partial thermal action or incomplete combustion while maintaining its fat content (Cerdà, García-Prósper, and Serra 2005).

Thermal alteration has been observed on every type of skeletal element, albeit with a definite predominance on the long-bone shafts of medium- and small-sized ungulates. Degree 3 represents the most abundant damage, followed by degree 2, while degrees 1 and 5 are the least represented (Blasco et al. 2014, 2016a; Stiner, Gopher, and Barkai 2011). Some specimens bear “sandwich” coloration predominantly on the long bones. The presence of burning on bone fragments might reflect several phenomena. The challenge is certainly to identify roasting (e.g., Alhaique 1997; Solari et al. 2015; Speth 2006), as other intentional processes could lead to burning, such as the removal of waste for cleaning purposes (e.g., Yravedra and Uzquiano 2013), the use of bone as fuel (Morin 2010; Théry-Parisot 2002), the preparation of bones to facilitate their breakage (Caceres et al. 2002), or the preparation of bone marrow for removal (Oliver 1993; Speth et al. 2012). Burned bones could also be the unintended (accidental) consequence of postdepositional damage such as secondary burning when fireplaces are set up on bones buried close to the surface (e.g., Aldeias 2017; Bennett 1999; Stiner, Kuhn, and Surovell 2001).

The task becomes complicated when several of these processes occur during the formation of the same sedimentary package. The superposition of different processes could mask the initial hominin activities, such as the roasting of meat before defleshing. As in the case of tortoises, we have tried to detect differential burning patterns on ungulate bones, that is, double colorations on the cortical surface and no alteration on the medullary surface, as it is expected that if bone is exposed when meat is on the fire for roasting, the medullary surface will remain unchanged and the exposed areas (or those covered by only a thin meat layer) will be affected more intensely by the heat, thus acquiring a higher degree of coloration (Gabucio et al. 2014; Gifford-Gonzalez 1989; Rosell et al. 2012). Despite complexities, a pattern based on the absence of burning on the medullary surface of ungulate limb bones was observed at Qesem. This pattern appears on bones that do show heat alteration (uniform or double coloration) on their cortical surfaces (7.32% of specimens bearing differential burning patterns from the hearth archaeological context). In addition, some of these bones (2.1%) show a higher degree of burning on those parts that would normally be exposed to fire when bone is placed on the embers to roast the meat adhering to it (e.g., metaphysis). This fact has been interpreted as the result of episodes related to roasting.

The roasting “signal” could be viewed as weak if we assume that only one fire-related activity occurred in the cave. However, the development of a single activity is unlikely to be iden-
ified for the following reasons: (1) the presence of burned bones over the entire excavation surface and volume, (2) alterations affecting all bone surfaces (both medullar and cortical), (3) structural changes of the bone tissues resulting from intense exposure to fire (e.g., fissures, cracking, shrinkage), and (4) significant concentration of burned material in the area of the fireplace (which includes the highest degrees of thermal alteration [calcined bones degrees 4, 5]). In relation to this, Mentzer (2009) proposes that the bone fragments become completely calcined when they are directly exposed to flame. This might occur when bones are thrown into the hearth for cleaning (Yravedra and Uzquiano 2013), when fireplaces are set up on unburied or semiburied bones (Bennett 1999), or when bones are used as fuel (Costamagno et al. 2009). As noted in Blasco et al. (2016b:204), these possibilities are not mutually exclusive, as many processes may have occurred concurrently or sequentially, leading to the overlapping of bone alterations and even to the destruction of elements or signatures after a specific primary human activity. For example, some burned bones show no homogeneous degree 2 coloration (brown), which coincides with alterations described by Bennett (1999) of specimens burned after burial, indicating nonnutritive episodes that occurred following the processing sequence. The set of thermal alterations at Qesem certainly shows the complexity of its taphonomic history, where more than one fire-related process, roasting included, seem to have occurred.

The case of *Testudo* sp. is particularly significant because 52.9% of the burned tortoise bones from the central hearth showed thermal alteration on different surfaces, and the highest degree of burning was observed on the dorsal surfaces. This pattern was especially pronounced in the earliest levels of the cave, as 83.33% of the double-colored bones showed a higher degree of burning on the dorsal than on the ventral surface, which tends to appear unburned (Blasco et al. 2016b). Although a certain degree of variability is to be expected, this pattern fits well with the idea of roasting tortoises by placing the whole animal upside down directly on the embers and allowing it to cook in the shell. These taphonomic patterns can be used as examples of new human-fauna relationships during the AYCC, which include cooking as a regular component of the human’s behavioral repertoire.

**The Organization of Human Activities around the Central Hearth: The Faunal and Lithic Evidence**

Spatially, the central hearth is an evident focus of intensive activities and is very dense in both faunal and lithic finds. We focus on the hearth itself and the area adjacent to it to the south, which seems to be related to the hearth (Blasco et al. 2016a; Shahack-Gross et al. 2014). A preliminary spatial analysis of faunal remains in this area has recently been attempted (Blasco et al. 2016a), and the lithic spatial distribution is under study.

The abundant thermally altered items lead us to infer a well-implemented use of fire at Qesem through its whole stratigraphic sequence. The central hearth area has been used here as a model to analyze and elucidate this behavioral pattern (Blasco et al. 2014, 2016a). The succession of cycles of combustion at the same location in the cave suggests a repeated behavior and a patterned use of space during recurrent human occupations. This resulted in a significant quantity of faunal and lithic remains as well as evidence of the spatial differentiation of activities around the hearth. The hearth and the area south of it cover an area of approximately 15 m² excavated to a maximum depth of 60 cm. The faunal assemblage comprises 37,304 specimens (2,995 specimens, or 8.03%, have been identified to the species level) of which 15,464 come directly from the hearth and 21,840 from surrounding zones. The faunal assemblage includes 15 taxa and a minimum number of individuals (MNI) of 81 (fallow deer MNI = 41, red deer MNI = 8, horse MNI = 6, aurochs MNI = 3, wild pig MNI = 3, wild ass MNI = 3, rhinoceros MNI = 2, goat MNI = 1, roe deer MNI = 2, large bird MNI = 3, Carnivore MNI = 1, Cervidae MNI = 2, and the tortoise MNI = 4; Blasco et al. 2014, 2016a).

Perhaps one of the best examples of spatial differentiation is the plot based on the size of bone fragments in the assemblage and the degree of thermal alteration of the bones. Density maps were generated using geographic information systems (ArcGIS 10) and include proximity calculations such as kernel estimation or the nearest neighbor algorithm (see details in Blasco et al. 2016a). Burned bones, mainly those showing a higher degree of damage (degrees 4 and 5), are clustered in the main combustion area. In contrast, the area around the hearth makes up less than 1% of the total number of specimens retrieved with this degree of damage (Blasco et al. 2016a). This apparent organization of the remains is most obvious if we consider the length of the bone fragments. Although the smallest specimens (<20 mm, the most abundant in the assemblage) are distributed over the entire occupied surface, the highest concentration is observed in the hearth area. Yet a most significant observation is the distribution of large bone fragments (>40 mm) in the outer area (Blasco et al. 2016a). This spatial distribution seems to fit roughly with the model of cultural formation of hearth-related assemblages observed by Binford (1978, 1983) in Nunamiat camps. The drop area is characterized by small bone splinters and lithic fragments resulting from different domestic activities, such as bone breakage for marrow extraction or the processes of core reduction and stone tool shaping. The toss zone, in contrast, consists of larger fragments that have been intentionally tossed away to areas farther removed from the activity areas. On this basis, a tentative standardized pattern can be observed along the sedimentary formation of the hearth. Both the spatial distribution around the hearth and the subsistence strategies can be considered as factors linked to the emergence of reference places of a residential character—that is, places that would fit with the concept of the home base discussed by Rolland (2004).

Results of spatial density data based on a study of lithics at 18 assemblages throughout the stratigraphic column and in different parts of the cave included the fireplace area and the area to its south (see Gopher et al. 2016). When lithic densities
of the hearth area and the area to the south of it are compared with the studied assemblages throughout the cave or, more specifically, with four assemblages of similar stratigraphic position and roughly contemporary, some interesting results are evident. The lithic assemblage of the hearth area consists of 18,837 items and shows the highest density of all the assemblages of the cave (6,144 lithic items per m\(^3\) for the hearth itself; see Gopher et al. 2016), indicating intensive lithic production, use, and discard in this area. This is reflected in the relatively high density of cores and core trimming elements (CTEs) as well (61 and 121 per m\(^3\), respectively). The area to the south of the hearth is somewhat lower in density (3,106 items per m\(^3\)) but shows high densities of cores and CTEs (37 and 63 per m\(^3\), respectively). A conspicuous aspect of the hearth area and the area south of it is the high density of cutting tools, including blades and naturally backed knives (NBKs) made on blades (both showing a density of 77 per m\(^3\)) as well as NBKs made on flakes that are prominently dense in the area (98 per m\(^3\)). Another outstanding aspect is the fact that the highest density of recycling is evident in the hearth area, including both the recycled “parents” and the recycling products (45 and 142 per m\(^3\), respectively), and south of the hearth (32 and 134 per m\(^3\), respectively). Many of the products of recycling have shown meat-cutting use wear (Lemorini et al. 2015), and the relatively high density of blades and NBKs (Lemorini et al. 2006) in this area suggests that they could be interpreted as a set of meat-cutting tools (Barkai, Lemorini, and Gopher 2010) densely concentrated at the meat-roasting area. Interestingly, the hearth shows a medium-low density of shaped items (tools), while the area south of the hearth shows a very low density of shaped items. This may indicate a frequent use of unshaped items (mostly characterized by sharp edges) in the hearth area and south of it. We may add that while blades and other cutting tools (including recycling products) are conspicuous in the hearth assemblage itself and the area south of it, assemblages of similar stratigraphy to the west and northwest of the hearth are poorer in blades and NBKs, poorer in recycled items and recycling products, and richer in shaped tools, including a conspicuously high density of scrapers (27–43 scrapers per m\(^3\) compared to 6 and 5 scrapers per m\(^3\) in the hearth and the area to the south of it). This may indicate the use of blades and of recycling products in some areas around the hearth while scraper-related activities have taken place in other distinctive and separated (though nearby and contemporaneous) areas of the cave.

**Inhaled Charcoal in Dental Calculus**

Potentially inhaled and ingested materials were extracted from dental calculus of the Qesem humans, including, among other things, microcharcoal, starch molecules, and *Pinus* pollen. These finds offer an insight into human diet and the environment around the cave, and the microcharcoal highlights the need for smoke management in the enclosed environment of the cave—a challenge introduced after adopting the habitual use of fire for roasting/cooking by the Qesem humans. Charcoal microparticles up to 70 μm in diameter enter the mouth during oral breathing, and while these fragments could also result from ingestion of char adhering to roasted food, their size suggests they result from accidental inhalation (Hardy et al. 2016). These findings, combined with the sedimentary and micromorphological evidence from the cave, are indicative of fire and suggest a smoky atmosphere inside the cave. While placing the hearth in a central place well inside the cave may be linked to the increased intensity of roasting/cooking, flint knapping, animal processing, and most, presumably, social interactions, the need for smoke management became necessary. A smoky atmosphere can be an irritant and can at times cause serious health problems. Smoke can cause coughing and eye irritation in addition to potentially more serious lung problems. For a successful use of fire to develop in an internal (cave) location and fulfill its potential functional and social purposes in a way that permitted the population to thrive, the health risks must be resolved.

**Discussion and Conclusions**

The Late Lower Paleolithic period in the Levant, and the AYCC in particular, was a period of transformation in human biology and culture. The habitual, common, and repeated use of fire for roasting meat (and possibly cooking in general) should be conceived as an integral part of this set of transformations rather than an isolated phenomenon. We believe that a better acquaintance with the environmental, behavioral, and adaptive contexts of the use of fire at ca. 400 ka in the Levant will promote comprehension of this new aspect and its significance in human evolution.

We claim that in the AYCC starting sometime at 400 ka, the use of fire was clearly aimed at meat roasting and possibly cooking in general, and this innovation continued in the Levant after the AYCC (see a statement on cooking as a Eurasian Middle Pleistocene innovation in Dennell 2009:476–477). A detailed discussion of the sociocultural aspects of fireplaces as central foci of human activity is beyond the scope of this paper (see Wiessner 2014), but the fact that a central hearth was exposed is of major importance in this respect. The use of fire at Qesem is first and foremost related to the dietary practices of the cave’s occupants. The diet of the Qesem inhabitants had a major meat component as reflected in the large number of animal bones and the dietary reconstruction we suggested (Ben-Dor et al. 2011). While floral remains were not preserved, we succeeded in extracting ingested floral remains from human dental calculus, including starch granules and chemical compounds, providing a direct link to ingested plant food containing essential nutrients, including polyunsaturated fatty acids and carbohydrates (Hardy et al. 2016). Following the sources on which we based our “fat hunter” model, a human diet based on meat and fat must have been complemented by carbohydrates and thus included three major ingredients: animal proteins, animal fat, and vegetal food. We have no
doubt concerning vegetal food consumption in the Paleolithic (e.g., Melamed et al. 2016), and the above-quoted study supports this view, providing direct evidence for the consumption of vegetal food. A point in order here are results of a study of masticatory wear patterns on human teeth carried out recently that provided evidence suggesting that the Qesem people possessed a strong masticatory system and fed on a wide range of food types (Sarig et al. 2016).

A major element in our argument has to do with the absence of elephants from AYCC sites. Elephants were part of the diet of Acheulian humans, and elephant bones, alongside other taxa, were found in Acheulian sites in the Levant throughout the 1-million-year span of the Acheulian Cultural Complex in the region. Elephant bones are present in early, middle, and late Acheulian sites (Ubeidiya, Evron, Gesher Benot Ya’aqov, Revadim, and Holon, respectively), and thus we may say that Acheulian human presence in the Levant is constantly associated with elephants and their use as a source of food. It is of course possible that elephants were not consumed at every Acheulian site and that in certain times and at certain places, Acheulian humans in the Levant survived with no elephant meat and fat on the menu. However, this was the exception rather than the rule. Sites of the AYCC as well as later sites in the Levant lack elephant remains. No elephant bones were found at any post-Acheulian site in the Levant, and they were not part of the post-Acheulian human diet, which was based on medium-sized, prime-aged animals both in the late Lower Paleolithic AYCC and the later Middle Paleolithic Mousterian (e.g., Speth 2012).

The significant changes in human behavior during the AYCC necessitated new knowledge-transmission mechanisms in order to cope with the many new aspects of behavior adopted. In addition to the production of flakes and bifaces, AYCC humans had to learn how to produce blades and Quina scrapers following strict standards. Moreover, knowledge and skills regarding the identification of flint sources and quarrying techniques and procedures had to be transmitted as well as the concept and practice of flint recycling. The focus on hunting prime-aged fallow deer (highest fat content) necessitated precise identification of specific deer to be targeted according to the color of the fur and the brightness of the skin. It is not without reason that the Saami of northern Norway, for example, use more than 600 words for describing reindeer according to their age, sex, color, coat, antlers, etc. (Clottes 2013). Tracking and hunting selected fallow deer must have been a practice based on specific knowledge and experience. Because we believe that Acheulian hominins hunted game including elephants and medium-sized animals, it goes without saying that parts of the tracking and hunting procedures of the AYCC were already practiced in the preceding Acheulian. However, because elephants contain large quantities of fat year round (Ben-Dor et al. 2011), fat-content-related choices had been marginal. When elephants were no longer consumed in the AYCC and later, it made a significant difference which deer was being hunted in order to supply not only meat but also fat, and thus new track-
Quina scrapers and small cutting tools made of recycled items might have been related to newly introduced processing methods (figs. 4, 5). Thus, the circumstances for the appearance of the AYCC in the Levant and its characteristics provide a context for the earliest manifestations of the habitual use of fire for roasting and cooking meat. The AYCC provided a context open for innovations and transformations, one of which was the adoption of fire. Such a major change in human behavior and lifeways must have been negotiated and carefully tested before being habitually adopted, and this is the case for many of the other transformations that took shape during AYCC times. We regard Acheulian human adaptation as highly successful and as having enabled Lower Paleolithic communities in the Levant to thrive for over 1 million years without using fire commonly and continuously and without roasting meat. Modifying this long-lived mode of adaptation and introducing a set of innovations such as the one characterizing the Levantine AYCC must have been for very good reasons. At around 400 ka in the Levant, human groups developed a new (post-Acheulian) adaptation mode that enabled them to thrive for another 200 kyr, until the next set of transformations took place, as reflected by the appearance of Middle Paleolithic Mousterian lifeways. We thus see the introduction, assimilation, and adoption of fire as a common human trait used for cooking meat as one of the innovative aspects that characterized the new post-Acheulian mode of adaptation in the Levant. This human trait must have been highly successful, as it characterizes human behavior and adaptation to this very day.

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Neanderthal Cooking and the Costs of Fire

by Amanda G. Henry

While it is clear that Neanderthals used fire for cooking their foods in some times and places, the record of their use of fire is somewhat patchy. We should not assume that Neanderthals had the same relationship with fire that we do; as a technological/cultural behavior, fire may be better understood as a tool that was used only when the costs of manufacture and maintenance were outweighed by the benefits.

Use of fire, particularly to transform food, is widely recognized as a major step in human evolution, allowing us increased access to refractive foods (Stahl 1984), lowered cost of digestion (Carmody and Wrangham 2009), and decreased exposure to food-borne bacteria (Smith et al. 2015). Just when this process was first adopted by human ancestors is highly debated, with the earliest evidence for fire being very unevenly distributed in time and space. Burned materials are found in association with hominin activity at a variety of archaeological sites, dating from 1.5 Ma at Koobi Fora (Hlubik et al. 2017), 1.4 Ma at Chesowanja (Gowlett et al. 1981), and 1 Ma at Wonderwerk Cave (Berna et al. 2012). However, as Pruetz and Herzog (2017) and Gowlett et al. (2017) indicate, naturally occurring fire is nearly ubiquitous, and it is extremely challenging to show that the hominins who created the archaeological scatters at these sites were coeval with, or even directly interacted with, the fire. To use the terminology developed by Sandgathe (2017), hominins may have been habituated to fire, but discerning their use, maintenance, or manufacture of fire is extremely difficult in the early record. In fact, regular use of fire does not appear to be widespread among northern-latitude hominins until much later (Roebroeks and Villa 2011; Stahlischmidt et al. 2015). Some have even argued that as late as the Middle Paleolithic, Neanderthals may have been able to maintain fires but were not able to manufacture them (Sandgathe et al. 2011). The benefits of cooking have been well documented (Wrangham 2009), and this has been argued to be a driving factor in promoting human use, maintenance, and manufacture of fire, such that once hominins first used fire, it quickly became an obligatory part of their niche. The disconnect between the very sparse archaeological record of fire and the potentially strong benefits of using fire begs the question, Is the absence of fire evidence a result of processes that erased the record of fire, or is fire use perhaps more variable in human history than we have previously assumed?

In this paper I address the question of Neanderthal use of fire, in particular for cooking their food. The fossil and archaeological record of Neanderthals is the most complete among our hominin relatives, and there is clear evidence at many sites that Neanderthals used fire and cooked their food. Despite this wealth of data, many questions about Neanderthal use of fire remain unanswered, and some have even suggested that fundamental differences between Neanderthal and Early Modern Human (EMH) use of fire may have contributed to the disappearance of the former. By exploring the factors that may have influenced how, when, and why Neanderthals used fire, we may begin to build a more nuanced model of the influence of fire in human evolution.

Evidence for and against Neanderthal Use of Fire

Several European and Levantine Middle Paleolithic sites have ample evidence for the presence of fire, in the form of discrete hearths of charcoal, ash, and fire-altered sediments, charred and calcined bone, and heated stone. These sites are found in the Levant at Tabun, Kebara, and Hayonim (Goldberg 2003); in France at St. Césaire (Morin 2004), La Quina (Chase 1999), Pech de l’Azé IV, and Roc de Marsal (Goldberg et al. 2012); and in Spain at Abric Romani (Vallverdú et al. 2012) and El Salt (Gómez de la Rua et al. 2010). Evidence for the use of fire includes the discovery of birch tar hafting, which would have required intentional heating (Mazza et al. 2006), found on several Middle Pleistocene flakes from Italy. The study of charcoal and other fire remains, though initially used to document the local tree species, has become increasingly used as a means to document Neanderthal and EMH fire behavior, in large part due to the extensive experimental works of Isabelle Théry-Parisot. She has shown that it is possible to differentiate among the burning of green, dry, and rotten woods, and that each of these fuels burns for a different amount of time with different heating properties (e.g., convection, conduction, and illumination; Théry-Parisot 2001). Applying these methods to ar-
chaeological sites, she has demonstrated that Paleolithic hominins (Neanderthals and EMH) generally burned dry standing wood and did not appear to choose particular tree species. However, she and others have also shown that in certain cases, Neanderthals burned coal or bone in addition to wood because of their preferred burning properties (Dibble et al. 2009; Théry-Parisot and Costamagno 2005; Théry-Parisot and Meignen 2000). Coal does not produce flames, but it is better than wood at conduction, so it is good for heating opaque, solid objects (e.g., food placed on the fire to cook or flint and other raw materials to improve their flaking characteristics; Théry-Parisot and Meignen 2000). Mixes of bone and wood achieve longer burning times and better conduction of heat than wood alone (Théry-Parisot and Costamagno 2005). These results strongly indicate that Neanderthals not only knew how to maintain a fire but had sufficiently experimented with different fuels to be able to choose among them to create fires with particular burning properties.

In contrast to the above data, there is also an increasing emphasis on the evidence that suggests that Neanderthals perhaps were able to use and maintain fire but were not able to manufacture it. Sandgathe et al. (2011) point to the fact that, once fire appears in the archaeological record, it is seen only at a small percentage of sites at any one particular time period and often only within a small percentage of occupation layers within each site. Based on the record at two French sites, they reject taphonomic processes, sampling biases, changes in function of the site, or seasonality of use as causes for the apparent disappearance of direct and indirect evidence of fire. They argue instead that the absence of fire reflects that the use of fire was “not an essential part of [Neanderthal] behavior” (Sandgathe et al. 2011:217). They emphasize that modern or recent historical foragers should not be taken as direct analogues for Neanderthals; instead, we must recognize that Neanderthals had a deep time history in Europe that may have provided ample opportunity to physiologically adapt to colder temperatures and to acquire enough calories from uncooked food. They conclude that Neanderthals used and probably maintained fire when it was convenient and available on the landscape—for example, in warmer periods when fuel was abundant and natural fires from lightning strikes were frequent—but that Neanderthals did not have the ability to manufacture fire.

Neanderthal Use of Fire for Cooking

In the same manner that Neanderthal use of fire has a variable record, evidence for cooking is inconsistent and debated. The cooking of animal foods such as meat and fat is mostly evidenced by heat-damaged bones. Blackened bones are frequently found in sites, but discerning whether they have actually been charred or just stained requires a level of analysis that was not commonly done during the excavation of many Middle Paleolithic sites (Shahack-Gross, Bar-Yosef, and Weiner 1997). Even for bones that have been conclusively charred or calcined, there can be some question about whether they were damaged during cooking, burned as a way of disposing refuse, or simply heated after burial when a fire occurred in the sediments above them. While some have developed metrics to help discern between cooked and otherwise fire-damaged bones (e.g., Costamagno et al. 2008; Speth and Tchernov 2001), these methods have been applied only to a very small number of Neanderthal sites. At Kebbara, it seems the charred bones were the result of cooking (Speth and Tchernov 2001), while at Pech de l’Azé IV, the evidence is inconclusive and could indicate cooking, refuse disposal, or both (Dibble et al. 2009).

Direct evidence for cooking of plant foods is extremely rare in the Neanderthal record. Charred seed remains have only been reported from a handful of sites, including Kebbara (Lev, Kislev, and Bar-Yosef 2005) and Douara Cave (Matsutani 1987) in the Levant, Franchthi Cave in Greece (Hansen 1991), and Gorham’s and Vanguard Caves in Gibraltar (Gale and Carruthers 2000). Most of these assemblages are very small, but the Kebbara assemblage consists of more than 4,000 charred seeds, mostly from legumes (Fabaceae) and nuts (Pistacia and Quercus). A range of other plants, including members of the Boraginaceae family, were also common at several sites. Though these have been interpreted as food, even charred seeds may not be an accurate record of cooking. Miller (1984, 1996) has strongly argued that the primary mechanism by which whole seeds become charred is by the burning of animal dung as fuel, rather than direct cooking of plant foods, since there is little benefit to be had by cooking whole seeds on an open-flame fire. Even if Neanderthals did not collect and burn dung, it is possible that the seeds were accidentally burned rather than intentionally cooked. Shallowly buried seeds may be inadvertently charred when a fire is burned above them (Aldeias et al. 2016), calling into question the relationship between the fire and the seeds. New sources of information about cooking and the consumption of cooked plant foods are clearly needed.

In the last 10 years, dental calculus has been increasingly explored as a source of new information about diet and health. This biological material is created through the proliferation of oral bacteria on the teeth and the subsequent mineralization of this biofilm due to the supersaturation of calcium phosphate in the saliva (Jin and Yip 2002; Lieverse 1999). The mineralized surface is recolonized by bacteria, and calculus builds up in successive layers throughout the lifetime of the individual, though the trigger of the mineralization process and the rate of formation are generally unknown and likely vary among individuals. As calculus forms, many of the organic residues found in the mouth, including human and bacterial proteins and DNA, food lipids, and plant microremains, are trapped in the mineral matrix and can be preserved over archaeological time spans (Buckley et al. 2014; Henry and Piperno 2008; Warinner, Speller, and Collins 2015). There are two types of plant microremains that are particularly useful in reconstructing diets—phytoliths and starch grains. Phytoliths are particles of amorphous silica that form within and between the cells of a plant (Piperno 2006) and are generally regarded as a form of mechanical defense against herbivory (Massey and Hartley 2006).
Starch grains are structures that a plant produces from long-chain carbohydrates as a means of energy storage (BeMiller and Whistler 2009). Both microremain types can have taxon-specific morphology that can be used to identify the plant species and/or plant part in which they were formed. Furthermore, plant microremains can often record changes due to processing, such as grinding and heating. Exposure to extremely high temperatures can change the refractive index of phytoliths (Elbaum et al. 2003), while starches can undergo a variety of diagnostic changes, including gelatinization, cracking, and loss of organization, which indicate heating in the presence of water (Babot 2003; Henry, Hudson, and Piperno 2009; Messner and Schindler 2010).

To date, over 70 Neanderthal dental calculus specimens from more than 40 individuals have been sampled for plant microremains and other residues, providing us a new glimpse into their dietary behavior (Hardy et al. 2012, 2016; Henry 2010; Henry, Brooks, and Piperno 2011; Salazar-García et al. 2013). These samples include material from the Levant (Shanidar, Qesem Cave), the Mediterranean (Sima de las Palomas, Kalamaki), and more "classic" areas in western Europe (Spy, La Quina, La Ferrassie). Some of the earliest work demonstrated that Neanderthals from a variety of environments consumed plant foods, including several of the resources, like grass seeds and tubers, that became important in later agricultural societies (Henry 2010; Henry, Brooks, and Piperno 2014). In rare occasions, gelatinized starch grains were found, indicating that the plants had been cooked prior to consumption (Henry, Brooks, and Piperno 2011). In the cases where the partially gelatinized starches could be identified to taxon, they seem to be all from grass seeds or other plants with hard, starchy endosperm in their seeds, lending support to the interpretation that the charred macrobotanical remains found in other sites do indeed represent cooking of seeds. However, this interpretation must be tempered by some of the unresolved issues relating to differential survival of starches from different plants.

Furthermore, it is interesting to note that many of the Neanderthal samples did not preserve any plant microremains. This pattern, with some specimens showing heavy use of plants while others seem to preserve none, has been found in every subsequent study of calculus, across the entire geographic range of sampled specimens. In fact, there has been to date no coherent pattern of plant use across the sampled specimens. Neither age nor geographic region influences the number of recovered plant microremains, nor the number of different types of plants represented (Henry, Brooks, and Piperno 2014). A study currently under way (Power et al., forthcoming) aims to explore whether a finer-grained geographical analysis that includes information about average temperature and tree cover at a site might better explain the number of plants that Neanderthals consumed. Particularly relevant to the discussion of cooking, however, is the observation that gelatinized starches are extremely rare and appear only in a small handful of specimens. While this may indicate even lower frequencies of cooking, again, we must be careful with the problem of absence of evidence—gelatinized starches are particularly vulnerable to removal from the archaeological record. Other calculus inclusions, including smoke residues, charcoal, and altered fats found in several individuals from El Sidrón and Qesem Cave, also suggest cooking by these individuals (Hardy et al. 2012, 2016).

There is much work to be done to assess the taphonomic biases that may affect the record of plant microremains and other residues in dental calculus. Based on studies matching the diets of modern groups with their calculus microremains (Leonard et al. 2015; Power et al. 2015), we know that our results likely underrepresent the true number of plant foods consumed by Neanderthals. Furthermore, there are many taphonomic factors that potentially remove starches from the archaeological record (Henry 2015), and we have seen that gelatinized starches are very quickly removed from buried stone tools (Debono Spiteri et al. 2014) and thus might also be strongly underrepresented in the calculus record. Residue analysis using mass spectroscopy–based methods is still in its infancy, as no analysis on populations with known diets has been performed. However, given the increasingly large number of Neanderthal calculus samples studied to date, it is likely that the apparent pattern of variability in Neanderthal use of cooked plant foods is a real one.

Applying a Behavioral Ecology Framework to the Discussion of Fire

When combined with the data that suggest inconsistencies in Neanderthal control of fire, the pattern of cooking variability raises the question of why Neanderthals would have fire and cook with it in some places and times and not in others. Some have argued that Neanderthals did not possess the capacity to manufacture fire (Dibble et al. 2017; Sandgathe et al. 2011), while others have invoked a more taphonomic explanation (Gowlett and Wrangham 2013). However, in most studies so far, researchers have considered only the possibility of an "either/or" situation—either Neanderthals had the ability to manufacture fire and therefore did so in all times and all places, or they did not. I propose that the use of fire needs to be examined using an explicitly economic framework to understand the benefits but also the potential costs of manufacturing and maintaining a fire. The relative costs to benefits in different environments could explain the variability in Neanderthal fire use. Neanderthals may have had the ability to manufacture fire but in some cases may have chosen not to do so, and it is in exploring their choices that we gain a better understanding of their behaviors.

Like other technologies, the use of fire for cooking is something that can be explained by using models derived from human behavioral ecology (Bird and O’Connell 2006). In these models, it is possible to predict an individual’s response to its current environment. The basic premise is that an individual attempts to achieve some goal that will increase its fitness, but in order to do so, it has to choose between a variety of potential
behaviors. Each of these behaviors has costs and benefits that are measured in a certain currency. In some cases, the individual is prevented from using one of its potential behaviors. When using behavioral ecology models to examine real-world data, the researcher makes a prediction about the exact goals, choices, costs and benefits, currencies, and constraints that influence the organism in order to predict the most optimal behavior. When the hypothesis matches the actual behavior, the researcher chose the correct variables; when the actual behavior differs from the predicted, then either the predicted variables were incorrectly chosen or the model was in some way inappropriate. This framework makes it possible to test whether certain environmental restrictions or behavioral limitations strongly influenced human use of fire, or we need instead to invoke another explanation (e.g., taphonomic bias, cultural pressure sensu Wiessner [2014]) for the presence or absence of fire in the archaeological record.

Specifically, in the case of using fire for cooking, most of the benefits come in the form of caloric savings. Several experiments have documented that some tubers, meat, and even oil-rich seeds become more easily digestible once cooked (Boback et al. 2007; Carmody and Wrangham 2009; Groopman, Carmody, and Wrangham 2015). The risk of food-borne illnesses drops once foods are cooked (Smith et al. 2015). Some plant foods are only accessible to digestion after cooking, due to the reduction in toxins and other antifeedants (Stahl 1984). All of these benefits can be measured as an increase in calories available to the consumer through a reduction in the caloric costs of the food, a reduction in costs related to illness, or an increase in the number of potentially calorie-rich food sources, all of which would then allow more calories to be spent on other tasks (Atello and Wheeler 1995).

Despite these rather significant benefits, there may be occasions or environments where the costs of creating a fire outweigh the benefits of having one. The most obvious cost is that of collecting fuel (Ofek 2001). Dry standing wood is the preferred fuel for cooking, because rotten wood burns poorly and fresh wood requires significant time investment (6–36 months) to properly dry (Théry-Parisot 2001), which limits its use by mobile foraging groups. Dry standing wood is common in many forested areas, and Théry-Parisot and Meignen (2000) have calculated that there is enough deadwood within less than a kilometer radius of a site to burn four fires 24 hours a day for 6 months. However, these calculations were done for the site of Les Canalettes in France, which would have been surrounded by thick forest during the period the authors were analyzing. In other environments, wood may not be so abundant (Elton 2008). Some of the earliest analyses of human choice of fuel have argued that preferred dry standing wood can quickly become depleted, even in areas of relatively low population density (Shackleton and Prins 1992). A recent paper on fuel use in the Pavlov Hills region of the Czech Republic proposed that the Gravettian hunter-gatherers in the region would have quickly eliminated the naturally occurring deadwood, and it may have taken several generations (40–120 years) for the deadwood to regenerate (Pryor et al. 2016). Clearly, securing preferred fuel would have required some sort of behavioral shift. In the case of the Gravettian groups, the authors proposed intentional management strategies, such as geographic mobility and the deliberate killing of trees in advance, but for groups less dependent on fire than modern humans, it is possible that other adaptive strategies may have been used.

Many studies have documented how increasing the cost of fuel can change behavior. Among people living today, fuel collection requires a significant time and energy investment, with some households in rural Mexico spending nearly 4 person-hours per trip to collect fuel (Manning and Taylor 2014). Small decreases in forest cover are connected with large increases in the amount of time collecting fuel, with one study linking a 1% increase in deforestation to a 0.3% decrease in fuel consumption and a 0.6% increase in fuel collection (Kumar and Hotchkiss 1988). This may sound small, but it represents an extra 1.13 hours per day spent on fuel collection (Kumar and Hotchkiss 1988). Recent Kenyan agripastoralists chose to prepare more quickly cooked foods in times of fuel scarcity (van Wijngaarden 1984). Furthermore, while these agripastoralists often collected fuel in conjunction with other tasks (such as herding cattle), they recognized the costs of carrying the wood, preferentially leaving cut green wood to dry in public areas, thus potentially risking its loss, rather than carrying the heavy fresh wood back to the farm to cure (van Wijngaarden 1984). Patterns of fuel use are less well studied in foraging populations than among developing societies. Women and children are the primary fuel gatherers in most societies (Murdoch and Provost 1973), but there is a clear environmental variation in the value of and attitude toward fuel. Lee (1979:148) noted that for the !Kung San, “in the dry Kalahari firewood is rarely a problem. Dead wood is plentiful and even living wood is dry enough to burn instantly if put into a fire.” In contrast, the Mbendjele foragers in Congo-Brazzaville complain about having to cook beans, because they take too long and require too much wood (K. Janmaat, personal communication); despite the abundance of trees, good fuel is limited in a rainforest.

In the archaeological record, it has also been possible to recognize behavioral shifts resulting from the costs of fuel. A series of elegant studies have indicated that, as local wood resources were depleted by smelting, Bronze Age inhabitants of the Levant shifted to using more tin in their bronze because of its significantly lower melting temperature, which reduced their overall fuel needs (Kaufman 2013; Kaufman and Scott 2014). Even earlier in history, in the semiarid savanna of southwest Texas and Coahuila, Mexico, Archaic period inhabitants relied on lechuagueilla and sotol, two extremely refractive starchy plant resources that required intensive processing, mostly roasting in an earth oven for long periods of time. To create enough food for 1 day for a small group of four to five individuals required a minimum of 250 kg of wood (Dering 1999). This quickly depleted local fuel sources, and Dering argued that fuel and food scarcity, not water availability, led to increasing mobility among these foragers. Charcoal analyses at Mousterian
sites have already shown that Neanderthals were aware of the qualities of their fires and probably also aware of the availability of various fuel sources. Théry-Parisot and colleagues (Théry-Parisot 2002; Théry-Parisot and Meignen 2000) have argued that the introduction of coal and bone to wood fires significantly reduces the amount of wood that is needed to burn for the same amount of time, suggesting a need to reduce wood consumption perhaps due to a decreased availability of wood. Furthermore, the charcoal fragments at a Spanish Neanderthal MIS 5–4 site showed signs of radial cracking and fungal infestation of wood (Vidal-Matutano et al. 2015). The former indicates the burning of green wood and the latter of rotten wood, neither of which is a preferred fuel source (Théry-Parisot 2001), suggesting that perhaps the local environment had become depleted in standing drywood. These lines of evidence suggest that there may have been ample reasons for Neanderthals to consider the amount of fuel they consumed. Though there would have been wood in sheltered places around Neanderthal sites even during cold, dry periods, it is possible that the time and energetic costs of collecting this limited resource may not have been offset by the benefits of fire.

Though fuel collection is the major cost associated with fire, there are other potential costs to consider. These include the time spent curating a fire to cook the food, the potential loss of food to conspecific competitors, the removal of potentially beneficial bacteria, and the health risks associated with fire itself. Time allocation is a major aspect of energy allocation. For example, sitting around a fire while cooking food is a relatively low-energy activity, and it is time that cannot be spent on other, perhaps more fitness-enhancing, behaviors such as collecting additional food items. The cooked food also needs to be guarded from theft. Wrangham and colleagues (Wrangham et al. 1999) noted that cooked food is of increased value because it is more digestible; also, it has been collected and gathered to a central place and is therefore at risk to be taken by “scroungers.” The potential loss of food items should be considered when weighing the benefits of cooking. Not only are cooked items vulnerable, but the fire itself is a shared good that is at risk of freeloaders (Twomey 2013) who might use the benefits of the fire but not contribute to its maintenance. Furthermore, the process of cooking itself may produce harmful physical reactions. Cooking destroys bacteria, which can reduce foodborne illnesses. However, we are increasingly aware that humans can acquire adaptive genes from exogenous bacteria and assimilate them within functional members of the complex system of gut microbiota (GM; Smillie et al. 2011). One potent example comes from a group of Japanese people who have gained the ability to digest a type of refractive seaweed by incorporating genes from naturally occurring bacteria into their GM (Hehemann et al. 2010). Studies of non-Western rural and forager groups further indicate that the adoption of genes from environmental bacteria into the GM confers digestive benefits (De Filippo et al. 2010; Rampelli et al. 2015; Schnorr et al. 2014). Finally, the process of creating a fire and cooking carries intrinsic health risks. These range from the nutrient-reducing and potentially carcinogenic effects of the Maillard reaction, which occurs when food is browned or burned over a fire (Ledl and Schleicher 1990; Mottram, Wedzicha, and Dodson 2002), to the actual risks of injury or death from burning and the long-term health risks of smoke inhalation (Bruce, Perez-Padilla, and Albalak 2000; Smith et al. 2000). Recent genetic studies have shown that modern humans, and not Neanderthals, Denisovans, or living African apes, have a fixed derived variant of a gene (AHR) that reduces the deleterious effect of polycyclic aromatic hydrocarbons, a group of chemicals released in smoke and found on charred foods (Hubbard et al. 2016). This suggests that there was strong selective pressure among modern humans to avoid some of the negative health effects of fire. Another study found no evidence in Neanderthals for selection among a large number of detoxification genes toward alleles that were more protective against the ill effects of smoke (Aarts et al. 2016). It is unlikely that Neanderthals had an understanding of microbial horizontal gene transfer or of linking cancer risks to browned food. However, these invisible costs of cooking may have had a noticeable effect on longevity and disease state, leading to a decrease in fitness of groups who regularly cooked.

Finally, and perhaps most importantly, the costs and benefits of cooking vary among environments, so that the value of cooking would not be the same across the entire geographic and temporal spread of the Neanderthals. As mentioned above, the amount of available fuel depended heavily on the degree of tree cover and on the local distribution of other resources, such as coal. For example, the cost to access standing deadwood in a steppe environment may have been very high, while other fuels might not have been an option if the foragers were mobile (it requires a significant time investment to create and dry dung cakes or to cure fresh-cut wood). Furthermore, the kinds of foods available in different environments have different responses to cooking. Within a single food type, plant underground storage organs, there is large variation among taxa in their nutritional qualities and their changes in digestibility when cooked. One study of the glucose digestibility of tubers consumed by the Hadza foragers showed that of four species, one had improved digestibility when cooked, two had negligible changes, and one was actually less digestible after cooking (Schnorr et al. 2015). The Hadza can and do consume these plants when raw, and when they cook them, they do so for short (ca. 5 min) periods (Marlowe 2010). It seems that the Hadza cook the tubers to make them easier to peel, but not to predigest the starch inside them. This is in contrast to the tubers available in rainforest environments, which often contain harmful toxins that must be denatured by cooking (and sometimes more elaborate processing like leaching in lye) prior to consumption (Tanno 1981). Clearly, ascribing the value of cooking to one single factor can lead to misunderstandings of its use in human history.

Fire is so embedded in the way present-day humans live that it is hard for us to consider life without its benefits, including cooking, light, heat, and protection. However, given the immense time periods and significant environmental shifts in...
which Neanderthals lived, we must realize that using our present, or even the recent historical past, as a reference may not be appropriate. When the data suggest interpretations for Neanderthal interactions with fire that do not mimic our own, we must be open to the possibility that they had a different mode of living. Instead, models developed for studies of all living species, such as those derived from behavioral ecology, allow us to better understand Neanderthal behavior in terms of costs and benefits rather than social or cognitive abilities. Behavioral ecology models have been successfully used to explore Neanderthal decision-making in other areas (e.g., that the choice of llich raw material depends in no small part on the distance to the quarry and the difficulty of terrain to reach it [Browne and Wilson 2011; Wilson 2007a, 2007b]). A new comprehensive view of the costs of fire must be undertaken. While many of the potential costs cannot be directly compared to the potential gains of cooking, we can at least begin by exploring the caloric costs of fuel collection in different environments and exploring how much time and energy it requires to access different fuels (e.g., dry standing wood, green wood, etc.). A study that incorporates the various caloric costs of fuel collection in different environments and compares this to the relative caloric benefits of cooking local foods could illuminate why, or why not, Neanderthals chose to cook their dinners.

Acknowledgments

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Savanna Chimpanzees at Fongoli, Senegal, Navigate a Fire Landscape

by Jill D. Pruetz and Nicole M. Herzog

Savanna chimpanzees (Pan troglodytes verus) at Fongoli, Senegal, appear to be able to predict the “behavior” of wildfires of various intensities. Although most wildfires are avoided, even the most intense fires are met with relative calm and seemingly calculated movement by apes in this arid, hot, and open environment. In addition to reviewing instances of such behavior collected during the course of the Fongoli study, we also report chimpanzees’ use of burned landscapes during the dry season, when more than 75% of these apes’ home range may be burned annually. In burned areas, chimpanzees spent more time foraging and traveling than in unburned areas. Chimpanzees’ behavior in a fire context can help inform paleoanthropological hypotheses regarding early members of our own lineage and can provide insight into the ability of early hominins to conceptualize the behavior of fire and thus set the stage for our lineage’s use of fire.

Chimpanzees are frequently used as referential models to inform our knowledge of human evolution because observations of living apes, when coupled with archaeological, ethnographical, and paleoanthropological evidence, allow us to hypothesize about the behavior of extinct hominins (defined here as bipedal apes). Data on living apes can be especially informative regarding subjects such as the origins of fire use when the paleoanthropological and archaeological record is expectedly sparse. Using cladistic analyses of behavior, Pruetz and LaDuke (2010) argue that understanding the capabilities of living apes can help anthropologists identify traits that are derived and those that probably also characterized early hominins, that is, primitive traits for our lineage. Specifically, chimpanzees using more open habitats such as the mosaic savanna-woodland environment in southeastern Senegal face environmental pressures similar to those of early hominins who experienced increasing aridification and savanna expansions at or near 2.8 Mya (Cerling et al. 2011; deMenocal 2004, 2011, 1995; Wolde-Gabriel et al. 2009; Wynn 2004). This environmental shift influenced the structure of mammalian populations, including hominins, in eastern Africa (Bobe and Behrensmeyer 2004; Vrba 1995). Adaptation to this emerging mosaic habitat has been indicated as a driving factor in hominin evolution (Blumenschine 1986; Potts 1998; Reed 1997). As such, knowledge of their behavioral responses to the local ecology can inform anthropologists as to how living apes adjust to a hot, open, and dry habitat, data on which we are lacking relative to our knowledge of how monkeys adapt and adjust to such an environment (Pruetz and Bertolani 2009). This approach, when bolstered by a focus on general patterns of behavior dictated by specific ecological change (Vaesen 2014), can lead to predictions about probable ancestral responses to landscape fires and so provide the basis for hypothesizing possible archaeological or paleontological consequences of increased fire frequency.

Given the regularity of seasonal fires in southeastern Senegal, the Fongoli community of chimpanzees is an exceptionally well-suited group from which to build hypotheses regarding the earliest hominin interactions with fire. We previously reported the responses of these chimpanzees to wildfires in this savanna-woodland environment and put this behavior into the context of a referential model (Pruetz and LaDuke 2010 sensu Moore 1996). Ideally, using a relational form of a referential model (Moore 1996) in which savanna chimpanzee behavior is compared with chimpanzees living in forested environments helps control for the tendency to directly analogize chimpanzees as representative of early hominins. However, all other habituated chimpanzees live in forested habitats where fire is a rare and potentially catastrophic occurrence, such as has been seen with Asian great apes and large-scale peat fires (Nellemann et al. 2007). To date, little opportunity to examine great ape interaction with fire in contexts such as those perhaps experienced by early hominins has been available.

Chimpanzees at the Fongoli study site adjust their movements to the intensity and movement of wildfires during the late dry season, and because wildfires are regular and extensive at Fongoli, we suggested that chimpanzees here exhibit behavior in the face of wildfires that reflects the earliest cog-
The potential capabilities required of hominins for the use of fire (Pruetz and LaDuke 2010). Molecular and morphological evidence suggest that chimpanzees shared a last common ancestor with the human lineage 4–8 Mya (see reviews in Kumar et al. 2005; Langergraber et al. 2012), and making the parsimonious assumption that this is a primitive hominid (here defined as the clade including the Pan and Homo lineages) trait, such a capability would support the assertion that use of fire was a relatively early event in the hominin lineage. If so, better understanding savanna-chimpanzee interaction with fire and burned landscapes can help inform hypotheses regarding the context of early hominins’ exposure to and reaction to fire.

In addition to providing updated information on chimpanzee encounters with wildfires, we present data on their use of burned landscape during the dry season in order to test the hypothesis that Fongoli chimpanzees use such areas differently from nonburned areas in this savanna-woodland environment. The frequent burning at Fongoli is probably atypical in terms of the frequency with which early hominins would have encountered wildfire. Nonetheless, it gives us insight into the behavioral adjustments that an ape with a cranial capacity corresponding to modern hominins’ exposure to and reaction to fire.

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Table 1. Review of proposed deep-time steps/stages in fire control

<table>
<thead>
<tr>
<th>Source and step/stage</th>
<th>Associated behaviors/adaptations</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stages of fire domestication (Burton 2009):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approach</td>
<td>Approach fire, interact with food items altered by burning</td>
<td>6 Mya</td>
</tr>
<tr>
<td>Associate</td>
<td>Develop a cognitive relationship regarding the benefits of fire and seek it out; tending and spreading naturally occurring fires</td>
<td>4–6 Mya</td>
</tr>
<tr>
<td>Manufacture</td>
<td>Ability to create flames outside of naturally occurring fire events</td>
<td>&lt;250 kya</td>
</tr>
<tr>
<td>Three cognitive stages in the control of fire (Pruetz and LaDuke 2010):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptualization of fire</td>
<td>Understanding fire behavior under varying conditions; ability to predict fire’s movement, thereby enabling close contact</td>
<td>Before the human-chimpanzee split, ~6–10 Mya</td>
</tr>
<tr>
<td>Fire control</td>
<td>Ability to contain fire, provide or deprive the fire of fuel, and possibly the ability to extinguish fire</td>
<td>NA</td>
</tr>
<tr>
<td>Fire creation</td>
<td>Ability to start a fire</td>
<td>NA</td>
</tr>
<tr>
<td>Pyrophilic shifts in hominin evolution (Parker et al. 2016):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive pyrophilia</td>
<td>Resistant to the effects of landscape fire</td>
<td>Before the human-chimpanzee split, ~6–10 Mya</td>
</tr>
<tr>
<td>Active pyrophilia</td>
<td>Reliance on fire-mediated foraging improvements</td>
<td>After the human-chimpanzee split, &lt;6–10 Mya</td>
</tr>
<tr>
<td>Obligate pyrophilia</td>
<td>Dependence on fire and cooked foods for survival and reproduction</td>
<td>Before/coincident with emergence of Homo erectus ~2 Mya</td>
</tr>
</tbody>
</table>
tion to, or interaction with, direct exposure to fire exist, with some exceptions (table 2). While the data are at present limited (see Herzog et al 2014; table 1 for summary), nonhuman primates are perhaps the best organisms to examine in order to refine the differences between humans and other species. Specifically, primates can serve as referential models of how our earliest ancestors may have responded to fire, especially given our order’s emphasis on learning and cognition as well as the potential to identify homology in our taxon. We propose that chimpanzees at Fongoli can provide insight into a number of questions associated with fire use in hominins. First, do chimpanzees exhibit behavior like monkeys (Armelagos 2010; Berenstain 1986; Harrison 1983, 1984; Herzog et al. 2014, 2016; Jaffe and Isbell 2009), which are attracted to burned or burning areas? Second, what would the impetus for attraction to fire be in early hominins? Proximity to fire is, of course, a prerequisite for the ultimate use of it. Minimally, conceptualization of fire behavior would allow hominins to feed and range in areas prone to fire. Thus avoiding costs associated with the disruption of activity in landscapes subject to burning. Not insignificantly are the dangers associated with remaining in the vicinity of wildfires, where narcotic gases can compromise animals’ central nervous systems and cardiovascular systems, rapidly incapacitating an individual (Purser 1986). Notably, within three minutes, rapidly growing flames can reach heat and noxious gas levels threatening to humans (Purser 1986). Here, we present data on apes with opportunities much like those the earliest hominins faced before the innovation of fire use had taken place. Specifically, we provide new data on chimpanzee reaction to fire and these apes’ use of burned landscapes and discuss these results as they relate to early hominins’ interaction with fire as well as fire use by the genus *Homo*.

**Methods**

**Study Subjects**

The Fongoli chimpanzee community size is, on average, 32 individuals (2005–2014; Pruetz et al. 2015). The community has consistently contained more adult males (9–12) than females (7–9), but a large number of immature individuals also characterize the group (11–15). Adult males were used as focal subjects per the Fongoli Savanna Chimpanzee Project’s protocol. One focal subject was chosen each day, based on the previous month’s order, so that focal sampling was not completely random but depended on when males were observed the previous month, and observers attempted to follow this order. Male absence from the larger social group or loss of a focal subject meant that focal subject order varied monthly to some degree. Females are not targeted as focal subjects because of the slight but real risk of adult females being targeted to obtain infants for the pet trade (1 case in 15 years; Pruetz and Kante 2010). Females are fully habituated in the presence of adult males but are nervous around observers when encountered alone or in small parties.

<table>
<thead>
<tr>
<th>Species</th>
<th>Reaction</th>
<th>Context</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orangutan (<em>Pongo pygmaeus</em>)</td>
<td>Imitated humans’ fire making</td>
<td>Rehabilitant apes</td>
<td>Russin 2000; Russin and Galdikas 1993</td>
</tr>
<tr>
<td>Orangutan (<em>P. pygmaeus</em>)</td>
<td>Set bags on fire with lit cigarettes and used them to set more bags on fire</td>
<td>Captive ape</td>
<td>Osborn 1912, in Mitchell 1999</td>
</tr>
<tr>
<td>Bonobo (<em>Pan paniscus</em>)</td>
<td>Taught to make (with lighter) and use fire for cooking</td>
<td>Language-trained captive ape</td>
<td>Segerdahl, Fields, and Savage-Rumbaugh 2005</td>
</tr>
<tr>
<td>Chimpanzee (<em>Pan troglodytes</em>)</td>
<td>Ignore; display at and through campfire</td>
<td>Captive apes experimentally provided with campfire</td>
<td>Charmoy 1996</td>
</tr>
<tr>
<td>Chimpanzee (<em>P. troglodytes</em>)</td>
<td>Ability to light and extinguish cigarettes</td>
<td>Captives in zoo given cigarettes</td>
<td>Brink 1957</td>
</tr>
<tr>
<td>Chimpanzee (<em>P. troglodytes verus</em>)</td>
<td>Foraged burned seeds</td>
<td>Reintroduction of ex-captive apes</td>
<td>Brewer 1978</td>
</tr>
<tr>
<td>Chimpanzee (<em>P. troglodytes verus</em>)</td>
<td>Avoid, predict movement, navigate</td>
<td>Naturally occurring seasonal wildfires</td>
<td>Pruetz and LaDuke 2010</td>
</tr>
<tr>
<td>Rhesus monkey (<em>Macaca mulatta</em>)</td>
<td>Foraged burned coconuts in ashes of fire</td>
<td>Free-ranging, introduced population; details of fire not provided</td>
<td>S. Gouzoules, in Armelagos 2010</td>
</tr>
<tr>
<td>Vervet monkey (<em>Chlorocebus aethiops</em>)</td>
<td>Ignored</td>
<td>Controlled burn</td>
<td>Herzog et al. 2014</td>
</tr>
<tr>
<td>Reed frogs (<em>Hyperolius nitidulus</em>)</td>
<td>Avoided by moving into protective cover</td>
<td>Experimental exposure to sounds of fire</td>
<td>Grafe, Dobler, and Linsenmair 2002</td>
</tr>
<tr>
<td>Raccoon (<em>Procyon lotor</em>)</td>
<td>Avoided (≥400 m)</td>
<td>Controlled burn</td>
<td>Sunquist 1967</td>
</tr>
<tr>
<td>Meadow vole (<em>Microtus pennsylvanicus</em>)</td>
<td>Avoided above- and belowground; one death</td>
<td>Controlled burn</td>
<td>Gelsos, Schroder, and Bragg 1986</td>
</tr>
<tr>
<td>Rook (<em>Corvus frugilegus</em>), Eurasian Jay (<em>Garrulus glandarius</em>)</td>
<td>Anting behavior with burning embers or lit matches applied to feathers</td>
<td>Captive birds</td>
<td>Goodman 1960</td>
</tr>
</tbody>
</table>
Study Site

The Fongoli study site is located in a woodland-savanna habitat in southeastern Senegal (12°40N, 12°13W). The Sudano-Guinean vegetation at Fongoli is characterized by a grass understory that covers >90% of the chimpanzees approximately 90 km² home range. Grasses, such as *Pennisetum purpureum*, can grow more than 2 m in height, so the late rainy season and early dry season are characterized by poor visibility and more difficult travel, of which almost 100% is done terrestrial ally at Fongoli (Jill D. Pruetz et al., unpublished data). Grassland (tall and short) and woodland (including bamboo woodland) habitat types account for most of the chimpanzees’ home range. Closed habitats (gallery forest and ecotone forest) account for less than 5% of the range. Anthropogenic disturbance such as fields, villages, artisanal gold mines, and dirt roads make up approximately 5% of the Fongoli chimpanzees’ range.

The Fongoli site is characterized by significant heat stresses for apes. There is one long dry season (November–April) and a short wet season (June–September), with May and October being transitional months when some rain may fall. In 2014 and 2015, however, less than 50 mm of rain fell in June, but May 2014 was characterized by >50 mm of rain. Rainfall before 2010 averaged less than 1,000 mm annually, but between 2010 and 2015 rainfall has become more erratic, with some wet years of >1,000 mm and some very dry years. This pattern matches the drying (Galat-Luong and Galat 2005) and warming trend noted in the region (Hillyer, Armstrong, and Korstjens 2015) and has implications for further environmental pressures on primates here. Maximum temperatures at Fongoli exceed 40°C during the late dry season (Pruetz 2007), and chimpanzees are reduced to between two and four permanent water sources available during the peak of the dry season. In addition to almost daily drinking and therefore cyclic ranging among the few available water sources, chimpanzees’ activity also reflects the pressures of heat stress. They rest significantly during the day at this time and have been observed to move and feed at night (Pruetz and Bertolani 2009). Dry season fires therefore present an additional pressure that could be viewed as significantly negative if the fires interfere with travel, feeding and foraging, or even resting behavior.

Frequent fires characterize grasslands, including woodlands dominated by a grass understory (Veldman et al. 2015). At Fongoli, wildfires begin annually in October, and we estimate that at least 75% of the chimpanzee range is burned on average each year. The vegetation is fire adapted (Tappan et al. 2004), and most fires here are probably due to human activity. Fongoli chimpanzees, like most chimpanzees in Senegal, live outside of national park boundaries, where humans set fires to clear land for cultivation, to aid in hunting, and to aid in navigating the landscape at the end of the dry season when dead and dying grass makes walking very difficult. Fires are prohibited but still occur, and late dry-season fires are especially destructive to the vegetation.

Data Collection

Immediate encounters with fire. Previous data on chimpanzees’ encounters with wildfire ($n = 2$) from the 2005–2006 study period (Pruetz and LaDuke 2010) are included. New data collected by Pruetz from late 2006 through early 2014 follow a similar data collection format, but in two instances more detailed data on chimpanzees’ interactions with fire were collected using instantaneous sampling (see below). Because wildfires occur in the dry season (October–April), chimpanzees are subject to fire 7 months each year. Data presented here come from a total of 15 months, 8 months in the first half or early dry season (October 2010; November 2010; December 2008, 2010, 2011, 2012; January 2012, 2014) and 7 months in the latter half or late dry season (February 2008, 2013; March 2006, 2008, 2010, 2012; April 2006).

When we observed chimpanzees’ encounters with wildfires, we collected data on their reactions to fire. In several cases, we collected data on temperature and wind speed using a handheld Kestrel data logger. In two cases, we conducted systematic observations using 5-minute instantaneous sampling, where we recorded individuals closest to fire each 5 minutes and noted their behavior as well as proximity (in meters) to the fire. In most cases, however, we could not collect such systematic data, as observers also ensured that they maintained a safe distance from the fire and did not approach wildfires as closely as some chimpanzees. Observers also mapped onto the chimpanzees’ behavior so that they could safely navigate the wildfires and, given the tendency for smoke to obscure visibility, staying with chimpanzees was considered a more reliable solution to avoiding the fire than setting out alone and trying to move around it.

Use of burned landscapes. We collected data on chimpanzees’ use of burned landscapes from 2011 to 2015 during the dry seasons. Data collection in 2014 and 2015 was minimal following a travel ban due to risks from the Ebola epidemic, which began in the neighboring country of Guinea. Data collection on burned landscape use consisted of recording whether the focal subject used unburned, burned (focal subject was within a burned area of at least 20 m in diameter), and partly burned (focal subject was within an area of unburned and burned vegetation or the area burned was less than 20 m in diameter) areas. While 20 m may seem subjective, it was used to attempt to distinguish between purposeful use of a burned area as opposed to encountering a burned area by chance in a largely unburned landscape. We recorded data every 5 minutes (instantaneous sampling) during focal male follows, and an attempt was made to follow the focal subject from the time he exited his night nest until he made a new one at the end of the day.

We collected a total of 305 hours of focal data on 12 adult male subjects with a mean of 25 hours of data collected per male (range 6–49 hours per subject). We collected opportunistic data ($n = 10.25$ hours; mean 0.85 hours per individual).
on chimpanzees in other age-sex classes (7 adult females, 2 adolescent males, 2 juvenile females, 1 juvenile male) when focal subjects were out of sight in order to increase sample sizes. In these cases, we recorded the behavior of the nearest visible chimpanzee during the interim when focal male subjects were out of sight. These individuals were not targeted for follows, and a new male subject was chosen based on the previous month’s order if the original subject was not seen again for 20 minutes. We conducted analyses with and without these individuals in order to examine whether results might be skewed because of low sample size per individual (range 0.9–1.75 hours).

Variables recorded included (1) focal subject identity, (2) date, (3) time of day, (4) activity (feed/orage, travel, rest, social [agonism, affiliation], nontravel movement, vigilance [following Nishida et al. 1999]), (5) habitat type (gallery or ecotone forest, woodland, grassland, bamboo woodland, field/road; see Bogart and Pruetz 2011 for detailed definitions of habitat types at Fongoli), (6) fire condition (burned, partially burned, unburned), and (7) substrate used (arboreal or terrestrial).

Results

Immediate Encounters with Fire

We recorded chimpanzees’ direct encounter with wildfires a total of 18 times over the course of the 15-month study (tables 3–5), seven of which occurred during the late dry-season months of February–April. When chimpanzees encountered fires, they frequently traveled through burned areas, often minutes after a fire had passed through (figs. 1, 2). Overall, in encounters with wildfire, chimpanzees most often appeared to ignore fire (42% of scores given, n = 10; fig. 3). However, they also tended to avoid or leave (move out of sight of the fire) a burning area as well (29%, n = 7; fig. 3). Other attention to fire included monitoring its movement (21%, n = 5) and navigating (here defined as moving in close proximity or less than 50 m to wildfire) through or around the fire (17%, n = 4; fig. 3).

Fires are potentially most deadly in the late dry season, when even fire-adapted vegetation succumbs to burning, and fuel is especially dry. Chimpanzees at Fongoli ignored fires earlier in the dry season; late dry-season fires (fig. 3) were monitored more often. Chimpanzees were also more likely to avoid or leave a burning area in the late dry season, but they were observed navigating burning areas in the early dry season, although sample sizes are low (fig. 3).

Use of Burned Landscapes

According to box plot analyses (SYSTAT, ver. 13), three adult males were characterized by outlying data points in the unburned condition, which could possibly skew results. Pearson \(\chi^2\) analyses run with and without these males did not significantly affect the outcomes, so data for all male subjects were subsequently pooled in analyses. Because sample sizes for individuals other than adult males were small, we also examined the effect of these data on results via separate analyses.

Chimpanzees spent slightly more time in burned (38%) versus unburned (35%) or partially burned (27%) areas, but these data are not corrected for the availability of the different burning conditions. General activity (feeding, rest, travel, social behavior) differed according to the three burned conditions (unburned, fully burned, partially burned) both when all individuals were included (\(\chi^2 = 194.613, df = 6, P = .000\)) or when only adult male subjects were considered (\(\chi^2 = 219.163, df = 6, P = .000\)). Resting behavior occurred less often, but travel behavior occurred more often in fully burned areas (fig. 4). Individuals spent less time in social behavior or rest in burned or partially burned areas (40% of activity in each condition), whereas these behaviors were characteristic of unburned areas (58% of activity; fig. 4). Feeding was done most often in partially burned areas (47%) compared to burned (40%) and unburned (33%) areas (fig. 4).

Discussion

Current evidence for hominin fire use is confined to archaeological data (e.g., hearths; for a review see Gowlett and Wrangham 2013) and paleoanthropological data (e.g., cranial and gut morphology associated with ingestion of cooked foods; Carmody and Wrangham 2009; Fonseca-Azevedo and Herculano-Houzel 2012; Wrangham 2009; Zink, Lieberman, and Lucas 2014). As Burton (2009) points out, however, hominins exhibiting such evidence of possible fire use and association must have experienced the forces driving these adaptations for some time before their visibility in morphology. That hominins such as *Homo erectus* show adaptations potentially related to a shift toward cooked foods indicates a much earlier onset for both active and passive uses of fire (Burton 2009; Parker et al. 2016). Therefore, archaeological and paleontological data alone may be insufficient in identifying the steps leading up to visible evidence of fire manufacture. We and others (table 1) suggest several cognitive and behavioral steps as prerequisites to the ultimate control of fire. Using this logic, we propose that the evolutionary effects of fire use and association should appear in earlier stages of hominin evolution.

Systematic observations of the costs and benefits that landscape fires provide for primates living in fire-prone regions should lead to predictions about likely ancestral responses to landscape fires, including scenarios of how hominins might intentionally associate with burned landscapes. Savanna chimpanzees, in particular, serve as an exemplary model for two reasons: (1) their frequent exposure to fires may be similar to that of hominins also inhabiting an open mosaic savanna-woodland habitat, and (2) they appear strategically to use burned landscapes and exhibit cognitive abilities necessary for interacting with wildfires, which tentatively provides support for the early fire-use theory.
Table 3. Summary of encounters between chimpanzees and wildfires over 15 dry-season months at Fongoli, Senegal

<table>
<thead>
<tr>
<th>Encounter</th>
<th>Date</th>
<th>Dry-season period</th>
<th>Time of day</th>
<th>Individuals observed in vicinity of fire</th>
<th>Detailed description of chimpanzee behavior in context of fire</th>
<th>Behavior summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>March 14, 2006</td>
<td>Late</td>
<td>1210–1700</td>
<td>5 am, 2 im</td>
<td>Pruetz and LaDuke 2010</td>
<td>Monitor and eventually leave</td>
</tr>
<tr>
<td>2</td>
<td>April 1, 2006</td>
<td>Late</td>
<td>1149–1325</td>
<td>2 am, 2 af, 7 im</td>
<td>Pruetz and LaDuke 2010</td>
<td>Move ahead and monitor; eventually leave</td>
</tr>
<tr>
<td>3</td>
<td>February 27, 2008</td>
<td>Late</td>
<td>1928</td>
<td>7 am, 6 af, 11 im</td>
<td>Apparently ignore</td>
<td>Apparently ignore fire</td>
</tr>
<tr>
<td>4</td>
<td>March 12/13, 2008</td>
<td>Late</td>
<td>1912; 0626</td>
<td>9 am, 3 af, 3 im</td>
<td>On evening of March 12, fire burned in streambed (&lt;50 m) below chimpanzee nest site. On March 13, it appeared that fire had burned through nest site, including some grass and fallen leaves, although previous burn probably reduced intensity of this one (understory grasses and shrubs had been burned in January or February of this year).</td>
<td>Apparently ignore fire or at least do not abandon nest site</td>
</tr>
<tr>
<td>5</td>
<td>January 4, 2009</td>
<td>Early</td>
<td>1615</td>
<td>2 af, 1 im</td>
<td>Recent fire has burned through the area, with fuel still smoldering. Chimpanzees ignore it.</td>
<td>Ignore smoldering fire</td>
</tr>
<tr>
<td>6</td>
<td>March 23, 2010</td>
<td>Late</td>
<td>0920–1015</td>
<td>1 af, 1 im</td>
<td>After fire is heard WNW (vegetation popping and smoke visible), female with infant moves in opposite direction. Wind = 1.3 km/hour, temperature = 33.3°C. She initially moves away from fire but cuts back across streambed to N then E. Area E and S of streambed is dry, tall elephant grass. She abandons fig feeding and leaves area at 1015 hours. No wind, temperature 34.4°C.</td>
<td>Avoids fire then leaves area</td>
</tr>
<tr>
<td>7</td>
<td>October 19, 2010</td>
<td>Early</td>
<td>1814</td>
<td>1 af, 1 am, 1 im</td>
<td>Fire near charcoal kiln. Party travels through area, feeding and moving. No discernible reaction to fire.</td>
<td>Ignore</td>
</tr>
<tr>
<td>8</td>
<td>October 20, 2010</td>
<td>Early</td>
<td>1750–1820</td>
<td>6 am, 1 af, 1 im</td>
<td>Observer hears fire at 1750 hours and party passes to N of fire, about 200–300 m from smoke. Party crosses burned area at 1815 hours, using it as a travel corridor through the tall grass.</td>
<td>Avoid, use burned area as corridor</td>
</tr>
<tr>
<td>9</td>
<td>October 27, 2010</td>
<td>Early</td>
<td>1620–1655</td>
<td>4 am, 2 af, 2 im</td>
<td>Observer hears fire at 1620 hours to SE. Party feeding and moving. Chimpanzees feeding in baobab tree seem to watch the fire, which is 100–200 m away. Party leaves hurriedly at 1645 hours, either in response to the fire or perhaps a person approaching (though nothing besides their hurried behavior indicates a person is near). Adult male (alpha male DV) stops and scans the area frequently. Observer can smell smoke.</td>
<td>Vigilant, probably leave area</td>
</tr>
<tr>
<td>10</td>
<td>November 16/17, 2010</td>
<td>Early</td>
<td>1850 (November 16); 0600 (November 17)</td>
<td>7 am, 4 af, 10 im</td>
<td>Observer is about 630 m from nest site at Maragoundi (dry) streambed and can hear fire, which we also heard at nest site. Fire never reaches nest site. November 17: can see fire never reached nest site. Not heard this morning.</td>
<td>Ignore</td>
</tr>
<tr>
<td>Date</td>
<td>Time of Day</td>
<td>Dry-season Period</td>
<td>Individuals observed in vicinity of fire</td>
<td>Detailed Description of Chimpanzee Behavior in Context of Fire</td>
<td>Behavior Summary</td>
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<td>------------------</td>
<td></td>
</tr>
<tr>
<td>11 November 18, 2010</td>
<td>Early</td>
<td>7 am, 3 af, 4 im</td>
<td>Can hear fire of party at 1745 hours. Sounds closer at 1820 hours and upon leaving nested party (1903 hours). Observer finds fire about 400 m from their nest site. Fire is moving in that direction. Chimpanzees remained in this nest site.</td>
<td>Ignore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 November 20/21, 2010</td>
<td>Early</td>
<td>2 am, 1 af, 1 im (party 1); 4 am, 3 af, 9 im (party 2)</td>
<td>November 20: fire heard in distance to S at 1220, 1705 and 1903 hours. Finds party that fissioned at 1903 more than 1 km away. Observer encounters fire about 900 m from nest site of party 1 at 2007 hours. Fires burn throughout the general area. November 21: 0625 hours, nest site of party 2 apparently burned the previous day or during the night, but party remained at this nest site. At 1305, fire is heard closer, to the SW, but is never seen. Wind speed 1.7 km/hour, temperature 34.9°C.</td>
<td>Ignore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 November 27, 2010</td>
<td>Early</td>
<td>3 am, 4 af, 6 im</td>
<td>Fire heard SSW at 1805 hours. Fire burned up to the dry streambed where chimpanzees nested this night, burning up the short-grass grassland and woodland adjacent to the riverbed. Chimpanzees apparently ignored the fire, as they remained in their nests (observer spent night out with party).</td>
<td>Ignore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 March 8, 2012</td>
<td>Late</td>
<td>3 am, 2 af, 4 im</td>
<td>Party appears to have left Kerouani (dry) streambed because of large wildfire approaching near the end of the day.</td>
<td>Leave area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 March 9, 2012</td>
<td>Late</td>
<td>3 am</td>
<td>See table 5. Pass through area to feed after short period of vigilance; ultimately leave area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 March 31, 2013</td>
<td>Late</td>
<td>3 am, 1 af, 3 im</td>
<td>Fire &lt;50 m SW of chimpanzees, who ignore it. One adult male sleeps in cave at ravine’s edge as fire burns above. Average wind speed 2.2 km/hour, temperature 41.5°C.</td>
<td>Ignore fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 December 31, 2013</td>
<td>Early</td>
<td>12 am, 4 af, 7 im</td>
<td>Party passes within 100 m of fire on near side of Oundoundo (dry) streambed and then within 50 m of flames, with one individual within 25 m. Two adult females stop to eat bamboo pith. Small fingers of fire within 10 m as party travels through streambed area. At 1619, fire is heard at bottom of ravine, roaring through dry vegetation for about 10 minutes. Party sits at top of slope, waits.</td>
<td>Navigate in close proximity; ignore fire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 January 6, 2014</td>
<td>Early</td>
<td>6 am, 1 af, 1 im</td>
<td>See table 4. Rest, groom, and feed while waiting for fire to diminish/move; continue travel and feed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. Cases in which the observer detected fire via sound or smoke but no distance estimation could be given and where its presence was also ignored by chimpanzees are not included here.

* *am = adult male; af = adult female; im = immature.*
Preliminary data on Fongoli chimpanzees’ use of burned landscapes in their savanna-woodland environment can provide some insight into the hypothetical precondition relationships between pre-fire-using hominins and their environment. At Fongoli, chimpanzees traveled and fed in burned areas, which might be predicted if Fongoli chimpanzees use these areas to navigate rather than opting to travel through areas of unburned tall grass. Ease of access during the early dry season, especially, characterized burned zones. Additionally, travel occurred soon after a fire had passed, and chimpanzees’ behavior of resting and socializing in the vicinity of Hamdalaye ravine, within 20 m of flames. Flames are very small, but as taller flames erupt <10 m away, JM sits up and then moves down slope, and MM whimpers (this could be because of the fire, JM’s exit, or DV’s ultimate arrival). KL runs out to MM for grooming as DV moves in the opposite direction to JM. KL cries (probably because of DV’s movement).

Table 5. Detailed description of extended close encounter with wildfire by three adult male Fongoli chimpanzees, March 9, 2014

<table>
<thead>
<tr>
<th>Time</th>
<th>Reactions by individuals closest to fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300–1520</td>
<td>Wildfire is 500 m E, although smoke blocks out the sun periodically. Males feed here until 1500, when they rest for about 25 minutes.</td>
</tr>
<tr>
<td>1525–1555</td>
<td>VN leads travel toward wildfire, which is in the vicinity of Hamdalaye ravine. Males eat along the way.</td>
</tr>
<tr>
<td>1550–1555</td>
<td>Can hear the roar of the fire/flames at Hamdalaye ravine as we near it.</td>
</tr>
<tr>
<td>1600</td>
<td>Males skirt the edge of the fire, passing &lt;100 m from it. Males travel through unburned tall grass, arriving at ravine edge at 1607 hours.</td>
</tr>
<tr>
<td>1607–1614</td>
<td>BO eats figs about 35 m from fire’s edge. Flames are visible. VN and JM sit at ravine edge and watch fire. BO “hoos” periodically.</td>
</tr>
<tr>
<td>1615</td>
<td>Males descend ravine within 5 minutes of arriving.</td>
</tr>
<tr>
<td>1615</td>
<td>Males have crossed ravine to the unburned side and &lt;150 m from fire. Grass is still green at the bottom of the dry streambed where they crossed but dry and brittle on slopes. Males feed on figs.</td>
</tr>
<tr>
<td>1620</td>
<td>Males eat figs &lt;125 m from fire.</td>
</tr>
<tr>
<td>1625</td>
<td>Males eat figs &lt;150 m from fire.</td>
</tr>
<tr>
<td>1630</td>
<td>Males eat figs, but fire is &gt;150 m away.</td>
</tr>
<tr>
<td>1635</td>
<td>Males descend ravine again in area where neither side is yet burned, moving toward the opposite side. Fire is 200 m away. We pass small fires burning in ravine as we cross it.</td>
</tr>
<tr>
<td>1640–1650</td>
<td>Males begin travel away from ravine and are again in the presence of a large fire, 200–300 m W.</td>
</tr>
<tr>
<td>1655</td>
<td>Males stop to termite fish more than 300 m from fire.</td>
</tr>
<tr>
<td>1700–1715</td>
<td>Males continue heading N, away from fire and eventually fusing with other individuals at their main seasonal water source more than a kilometer away.</td>
</tr>
</tbody>
</table>

* Adult males BO, BN, JM.
cinity of wildfires indicated they can accurately predict the leading edges of fire and assess other aspects of fire behavior based on the available fuel in an area, which can move rapidly and vary greatly within a small space according to microhabitat variation (Trollope, de Ronde, and Geldenhuys 2004). In order to do so, they must take into account the following variables: resultant flame height and distance traveled, fuel and wind speed, and topography and climate. Understanding this complex set of interactions perhaps involves forming a mental prediction of the fire’s behavior (Pruetz and LaDuke 2010). We surmise that Fongoli chimpanzees are adept at predicting fire behavior because they often exhibit the appropriate responses to different fire types. They appear unconcerned regarding their frequent exposure to smoldering fires or early flaming fires, but they are more likely to avoid fully developed or postflashover fires (sensu Purser 1986).

If the many questions associated with hominins’ use of fire are simplified into (1) how, (2) why, and (3) when, using living apes as referential models can inform each of these. The observations presented here of the Fongoli chimpanzee community prove most informative in aiding hypotheses regarding how hominins may have taken advantage of exposure to fire such that an innovation ultimately led to use. This question corresponds with our first stage (table 1; Pruetz and LaDuke 2010), possessing the cognitive sophistication necessary to allow close contact with fire. Although the frequency with which chimpanzees at Fongoli, Senegal, must deal with fire is probably much higher than that of any early hominin, the fact that these relatively small-brained apes seem easily to incorporate navigation around fires and through recently burned areas supports the hypothesis that early members of our own lineage would have had similar abilities. Rather than fleeing from fire, they would have understood it as a force shaping their local ecology, incorporating its effects into their daily activities, such as continuing to feed and range within areas in proximity to wildfires as long as resources remained. Following from the assertion that living apes possess the cognitive sophistication necessary to allow close contact with fire resources, we argue from...
Figure 2. Adult female Fongoli chimpanzee moves through recently burned area. A color version of this figure is available online.

Figure 3. Chimpanzees’ reactions to fire according to dry-season period (late vs. early).
homology to support the hypothesis that fire use was an early rather than a later event. Much like the difficulty associated with identifying and interpreting transitional or newly derived traits in the fossil record, early hominin attraction to and their very first use of fire will be difficult to ever identify archaeologically or paleoanthropologically (see Gowlett 2016; Gowlett and Wrangham 2013; Herzog 2015; Parker et al. 2016). However, the capabilities of living apes indicate that even the earliest hominins would have been cognitively sophisticated enough to understand some aspects of fire behavior.

Regarding the question of why the earliest hominins may have been attracted to fire-modified landscapes, evidence suggests at least three possible motivations: (1) changes in the distribution of and access to food, (2) improvements in travel, and (3) decreased threat of predation. Dietary improvements, such as improved encounter rates with preferred prey (Herzog et al. 2016), have been shown for other primates. However, stable isotope studies, which provide the most appropriate assessment for comparing similarities between early hominin and chimpanzee diets, show an almost exclusive C3 plant diet for both before 4 Mya (Sponheimer et al. 2006, 2013), suggesting that fire many not alter the distribution of many key chimpanzee foods in the ways it does for other primates. Typical C3 foods, such as tree fruits, are less likely to be destroyed by wildfire than C4 grasses and other terrestrial herbaceous vegetation (THV), save in areas where tall elephant grass provides fuel of sufficient height to burn low tree branches. During much of the dry season at Fongoli, chimpanzees focus on baobab (Adansonia digitata) fruit (Lindshield 2014), which is rarely affected by fires. The majority of important chimpanzee dry-season foods (defined according to time spent feeding on these species) are tree fruits. One important fruit that is affected by fire is the liana, Saba senegalensis, which can be severely compromised by late dry-season fires, with fruit being destroyed even if liana survive (Jill D. Pruetz, unpublished data). Saba liana are found at various levels of the canopy.

However, certain food resources may be positively altered on a longer temporal scale. For example, fire can alter the phytogeography of certain plants, creating long-term positive alterations in distribution and abundance. During the month of October, chimpanzees at Fongoli feed extensively on Vigna vine legumes, which are a type of THV. While burning destroys these plants in the short term, it may increase encounters the next year by promoting greater plant propagation (Rebetzke and Lawn 2006).

Other foods important to chimpanzee dry-season diets include honey (Jill D. Pruetz, unpublished manuscript), which is almost always harvested from a tree hollow and frequently from the baobab tree, and the Macrotermes termite (Bogart and Pruetz 2011), which is protected from wildfire by its large termite-mound refugia. While isotopic data suggest predominantly C3 diets for hominins, they also demonstrate that in response to increasing aridity and climatic variability, some lineages probably targeted foods abundant in grassland settings, such as invertebrates, tubers, and the fruits and pods of arid adapted plants (Sponheimer et al. 2005a, 2005b). Fongoli chimpanzees live in a similarly arid environment and consume many of the same foods. For example, while still largely frugivorous, Fongoli chimpanzees spend more time obtaining invertebrates than any other chimpanzee population studied, with total foraging time dedicated to invertebrate feeding at times outweighing that of fruit (Bogart and Pruetz 2011). Observations among this population could shed light on the ways in which burning prompts increased insectivory (Burton 2009; Herzog et al. 2015), a shift nominated as fundamental in shaping our lineage (Bogart and Pruetz 2011; Burton 2009; McGrew 2001, 2014).

Savanna chimpanzees spend almost all of their total travel time moving terrestrially (Jill D. Pruetz et al., unpublished manu-
uscript). However, for chimpanzees, terrestrial locomotion is more costly than arboreal locomotion (Pontzer and Wrangham 2004). Therefore, among this population fire may have a two-fold effect on travel. First, the removal of an understory that is thick and difficult to move through may facilitate decreased travel time between patches. This phenomenon was observed among savanna-dwelling vervets, which not only expanded into burned areas traveling almost exclusively terrestrially but also moved faster in these areas than in unburned alternatives (Herzog et al. 2014). Second, these newly bare landscapes may simply impose fewer energetic locomotor costs than unburned alternatives. Chimpanzees in this study spent a higher proportion of time traveling in burned than either unburned or partially burned areas.

Finally, burned areas may be attractive because of enhanced predator detection in fire-cleared grasslands (Herzog 2015). In burned areas, vegetation that may have otherwise served as cover for ambush predators is gone. Without sufficient cover, predators may abandon efforts at hunting in these areas, and research has suggested that predators avoid burned habitats (Ogen-Odoi and Dilworth 1984; Eby et al. 2013; Green et al. 2014). At Fongoli, where approximately 85%–90% of the understory is grass, late rainy season and early dry-season travel is difficult. Chimpanzees have been observed taking advantage of recently burned areas as travel corridors, and it is possible that these areas also provide them greater safety in terms of predator detection and reduced ambush sites for predators.

The final question, when, will be the most difficult to answer. Recent archaeological and paleoanthropological reconstructions are notably at odds regarding the emergence of this important milestone in human evolutionary history (see Gowlett 2016). Regarding the early control versus late control theories of fire use (see Herzog 2015 for review), emerging data on nonhuman primates can at least provide an indication of what is and is not unique regarding our lineage’s relationship with fire. As Herzog et al. (2014) point out in one of the only other studies specifically designed to assess primates’ reactions to fires rather than post hoc or opportunistic inquiry, the fact that cercopithecines such as vervets (Chlorocebus aethiops) showed calmness in the face of wildfire indicates that such a prerequisite for eventual use could be a primitive trait for catarrhines at least. As more data emerge on the topic, a conceptual model (Herzog 2015) could add to the existing primate data, which has thus far been referential in nature. Attention to the particular behavioral ecology of candidate nonhuman primates to include would consider features of the diet and factors related to predator pressure, for example, that would be most informative when attempting to construct hypotheses regarding the emergence of fire use in the hominin lineage.

The use of fire is a uniquely derived trait that has been used to distinguish humans from all other animals alive today (Goudsblom 1986). However, considering scenarios that led to the use of fire by our lineage helps to shed light on the how and why of such events, which are notoriously difficult to identify without the use of behavioral models (either ethnographic, in terms of understanding later stages of fire use—see Holdaway, Davies, and Fanning 2017 and Mallol and Henry 2017—or using nonhuman primates to understand earlier stages of the precondition for fire use). Several authors (Burton 2009; Gowlett 2016; Gowlett and Wrangham 2009; Herzog 2015; Parker 2014; Parker et al. 2016; Pruett and LaDuke 2010) justify using primate models, especially apes, to understand the behavior of early hominins in respect to fire. They posit that ancestral fire use probably occurred earlier than definite archaeological evidence suggests. While anecdotal information shows that nonhuman primates do not exhibit fear of fire (summarized in Burton 2009), data are based on experimental contexts or human-produced campfires (table 2). Apes living in fire-prone areas, therefore, can present a more natural context for potential scenarios in which early hominins encountered natural fires and provide insight into the dynamics between a relatively small-brained hominin (i.e., preceding the genus Homo) and fire landscapes. If chimpanzees can be used as a referential model for small-brained hominins living in similar wooded savanna environments, we are one step further in better understanding the role that fire use had in our own genus.

Acknowledgments

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Pruetz and Herzog 2016. What modi...
This article explores a conception of the origins of fire as a process of shifting human interactions with fire, a process that, in a sense, still continues today. This is a counterpoint to the dominant narrative that envisions a point of “discovery” or “invention” for fire. Following a discussion about what fire is and how it articulates with human society, I propose a potential scenario for the prehistory of fire, consisting of three major stages of development. From this perspective, obligate cooking developed gradually in the course of human evolution, with full obligate cooking emerging subsequent to modern humans rather than synchronous with the appearance of Homo erectus as envisioned by the cooking hypothesis.

The study of human evolution is an undertaking that, like all great scientific challenges, requires a combination of empirical rigor, luck, creativity, and imagination. In On the Origin of Species Darwin wrote eloquently of the incompleteness of the fossil record, and this is certainly where a healthy dose of luck, and creativity, comes in handy. In the study of human evolution there is a particular problem posed by the structuring of time periods that span hundreds of thousands of years. While this excessively longue durée characterizes all of paleontology, and in fact from this perspective human evolution is very brief, there is good reason to think that there are challenges that are unique to the study of human ancestors. The Paleolithic lies at the hinge between paleontology and history. In studying our own ancestors we tend to rely on narrative structures that, although never completely absent, are somewhat more weakly expressed in other aspects of evolutionary research. Landau (1993) has demonstrated the relationship between scenarios of human evolution and tropes drawn from folktales, while Stoczkowski (1994, 2002) has elucidated the common structural characteristics of these narratives. The demands of contemporary media (web-based, television, and print) also play a major role in tunneling discussion toward a narrative with a single point of origin.

This article explores a conception of the origins of fire as a process of shifting human interactions with fire, a process that, in a sense, still continues today. This is a counterpoint to the dominant narrative that envisions a point of “discovery” or “invention” for fire. One way of phrasing this perspective is that there is not an “origin” of fire but, rather, a long prehistory of fire. I will begin by discussing what fire is and how it articulates with human society and then will present a potential scenario for the prehistory of fire.

From the perspective of evolutionary biology scenarios “are [phylogenetic trees] fleshed out with narratives of adaptation, competition, ecology etc.” (C. Patterson 1981:209). Tattersall and Eldredge have described a scenario “as an extremely intricate type of proposition” at a remove from testable hard data (1977:205). Most archaeological research proceeds based on the construction of scenarios that are at least in part inductive and at least potentially testable based on the archaeological record (Hodder 1999). The cooking hypothesis developed by Richard Wrangham also operates at the level of a scenario but it is important to recognize that the basis for the construction of the cooking hypothesis is fundamentally different from an archaeological approach. Wrangham and his collaborators work from the observation “that present-day humans cannot extract sufficient energy from uncooked wild diets” (Carmody et al. 2016:1091). From this observation, the logical inference is that obligate cooking must have a point of origin in hominin phylogeny. This point of origin is then mapped onto the increase in hominin brain and body size ca. 2 million years ago, leading to the proposition that obligate cooking began with Homo erectus and was a characteristic of subsequent taxa on the hominin lineage. The power of the approach taken by the cooking hypothesis is that it is at least partially testable based on experimental studies on the physiological and molecular correlates of consumption of cooked food (see literature cited in Carmody et al. 2016; Wrangham 2017). However, this approach also has a number of shortcomings. First, while obligate cooking necessarily must have a point of phylogenetic origin, the same is not true for cooking that might become integrated into hominin adaptation through a process rather than as the result of a single event. Second, while many aspects of human obligate cooking can be experimentally tested, there is no current method for testing whether H. erectus required regular cooked food. In fact, the placement of the onset of

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obligate cooking at 2 million years ago is not directly testable without recourse to the archaeological record (including recovery of residues from fossils; see Hardy et al. 2017).

Defining Fire

Fire is “a self-sustaining, high-temperature oxidation reaction which releases heat and light; and which usually needs a small input of heat [ignition] to get it going” (Rossootti 1993:5). Fire involves the combustion of fuel, which in the archaeological record is limited to organic compounds including wood, grass, fat, and bone. Combustion products such as ash and charcoal leave the material traces that, along with the burned substrate, can be observed in well-preserved archaeological contexts. Exposure to fire also causes fracture in siliceous rock such as chert, including caving and pot lids (L. W. Patterson 1995; Purdy 1975). Burning can also alter both the magnetic properties and the thermoluminescent signal of siliceous rock (Borradaile, Stewart, and Ross 1998; Richter, Alperson-Afil, and Goren-Inbar 2011). Burned bone can be identified on the basis of surface features such as color and of application of FTIR (Fourier transform infrared spectroscopy) (see Berna et al. 2007, 2012; Stiner et al. 1995).

There is a firm empirical basis for considering natural fire to have been part of the ecology of early hominins. Geological evidence of fire dates back to the Devonian (Scott 2000). Byers et al. (2014) provide evidence of a fire scar on a Triassic tree, suggesting that fire played an important role in plant ecology by the Triassic. There are also geological examples of fire associated with fossil fauna. For example, Brown, Collinson, and Scott (2013) examine the association of charcoal with Cretaceous hadrosaurs, ankylosaurs, and other fauna at Dinosaur Provincial Park in Alberta, Canada.

There is a wide body of literature on wildfires that aims to understand the factors underlying wildfires and changes in wildfire due to global warming, anthropogenic activity, and forest management. Average fire conditions, known as fire regimes, include fire density (number of fires within a given area), fire return interval, and fire intensity and severity (duration and radiative power) (Chuvieco, Giglio, and Justice 2008). The seasonality of fire is linked to both covarying and stochastic weather patterns including temperature, wind speed, relative humidity, and radiation—as well as frequency of lightning strikes (Johnson and Balice 2006). Analysis of fire records from giant sequoia groves in California links the frequency of fire to long-term climate change (Swetnam 1993). Despite the limitations posed by the human role in modern fire regimes, it is clear that from the perspective of early hominin ecology, fire can be considered to be a seasonal resource (for further data, see Archibald et al. 2010; Johnson and Balice 2006; Swetnam 1993; van Wagendonk and Cayon 2008; van Wilgen and Scholes 1997).

Fire in Human Society

In the context of human society, fire takes on multiple aspects that go beyond the physics of combustion or the dynamics of a seasonal natural resource. As Wrangham (2009) emphasizes, for modern humans, fire has become a necessity for life. In the context of human society, fire also becomes a technology, is deeply socially embedded, and can take on a spiritual dimension. As is often the case with significant aspects of human culture, these various dimensions of fire—adaptation, technology, society, and ideology—are often intertwined. To illustrate the functioning of fire in human society, a case study from the archaeology of complex societies is useful. The choice of an example from complex societies rather than the ethnographic record for hunter-gatherers is deliberate. The point is to emphasize that the relationship between humans and fire is an ongoing process that does not apply only to hunter-gatherers.

The Egyptians of the Old Kingdom, the period of pyramid construction, developed a distinctive technology for baking bread (Chazan and Lehner 1990). In this technological system a thick clay pot served as a small oven. What makes Old Kingdom baking particularly interesting is that scenes on the walls of Old Kingdom tombs, particularly the Tomb of Ti at Saqqara (fig. 1), provide a detailed account of how this technology worked, and excavations of bakeries near the Giza pyramids add an archaeological perspective (Lehner 1996; Mahmoud and Eissa 2015). It is interesting that the fire itself is not depicted in the scene from the Tomb of Ti, yet its effects are clearly evident in the actions of the figures crouched next to the oven, who protect their faces with their hands, and in the hieroglyph that indicates that it is hot. Also absent from the scene is a depiction of how the fire is made; however, it is safe to assume the use of some form of bow drill—a method used in Old Kingdom ground stone technology.

The scene found in the Tomb of Ti provides an unusually complete perspective on the dynamics of an ancient technological process. In Old Kingdom Egypt the production of bedja bowls, which are thick walled with an organic-rich fabric to resist thermal shock, and their use as ovens is a very particular technique. In this context fire is integrated into a chaîne opératoire of baking.

The technology of Old Kingdom baking is deeply integrated with the social structure of a complex society engaged in the construction of monumental architecture. Baking in bread molds allows for the centralized processing of grains into edible food, which removes food preparation from the household and thus frees labor for monumental construction. The baking of bread in molds also has the advantage of producing food as a commodity. By controlling the size of the interior of the bread mold, it is possible to create loaves that adhere to a tight unit of measure and that can be transported and distributed. In the Giza bakeries there are two sizes of bread mold, and the interior volume of the vessels was highly standardized through control of the rim diameter and depth of the vessel. It is not an exaggeration to say that the construction of the pyramids at Giza was dependent on the technological system that allowed a fire burning in a small, open oven to transform grain into standardized loaves of bread. It is also true that the way the flame in the bakery oven was integrated into a technological system is the result of the social structure of Old Kingdom Egypt.
The engine of the developments on the Giza Plateau was far from basic subsistence. The entire context, including the associated bakeries, makes little sense without considering the Egyptian beliefs about the divine nature of the king and the king’s body. There is, however, no indication that the fire in Old Kingdom bakeries was regarded as sacred. The Egyptians did have ideas about fire as an “effective weapon against . . . nightmares and other nocturnal agents of chaos” (Szpakowska 2003:121); however, there is no mention of such powers in the bakery scene in the Tomb of Ti.

In sum, while fire is a chemical reaction and a natural resource, it is also in the human context a technology, an aspect of society, a necessity, and an element of belief. Consideration of Old Kingdom baking allows us to recognize that the way fire is used to meet nutritional needs is highly contingent on both technology and social systems. While it might indeed be necessary that humans eat cooked food, the way this cooking takes place is highly contingent. In the context of Old Kingdom Egypt, the energetic requirements were not simply the requirements for survival and reproduction but also were demands to release a tremendous amount of labor from subsistence activities.

A Scenario for the Initial Development of the Human Use of Fire: A Long Prehistory

The available archaeological data are consistent with a scenario of three stages in the development of human interaction with fire during the Paleolithic. It is important to emphasize that this is a generalized scenario and that it is meant to highlight the major tendencies in the development of fire. The intention is not to negate the likelihood that there were localized developments that depart from these major tendencies. This scenario builds on the idea that the adaptive, technological, social, and ideational aspects of the use of fire are closely intertwined. It is built on the currently available archaeological data and thus is subject to testing and refutation. As noted above, this type of inductive approach is limited by the incompleteness of the archaeological record, and there is always the risk that the absence of evidence will be incorrectly interpreted as the absence of a behavior. However, the focus here is looking at patterning in the archaeological record over time rather than at particular observations in isolation, so that the absence of evidence is significant in relation to the subsequent presence of evidence.

Stage 1: Opportunistic interaction with fire dates back 1 million years but likely appears much earlier, perhaps even to the origins of Homo erectus. Fire at this stage was a seasonal resource, and maintenance of fire was limited.

Field observations suggest that chimpanzees are able to control their fear response to fire and thus show a degree of conceptual understanding of fire (Pruetz and LaDuke 2010). Evidence for interaction between hominins and fire before ca. 400,000 years ago is rare (for reviews of evidence, see Bar-
The site of Gesher Benot Ya’aqov (ca. 700,000 years BP) has produced evidence of low-intensity traces of fire in small patches within a dense scatter of lithics and fauna (Alperson-Afl, Richter, and Goren-Inbar 2007; Alperson-Afl et al. 2009; Goren-Inbar et al. 2004). If the pattern detected at Gesher Benot Ya’aqov can be replicated, that would suggest that early interactions with fire were short-lived—as any long-term maintenance would have produced a more pronounced signature, although the pattern of recurrent fireplaces in the same area requires consideration. There is no evidence from Gesher Benot Ya’aqov of the technologies associated with making fire, so this scenario is unlikely (see discussion below). If Gesher Benot Ya’aqov provides early evidence of collection of fire, this would suggest that in its early stages this behavior is not associated with practices for the long-term maintenance of fire.

At Wonderwerk Cave, South Africa, detailed micromorphological analysis combined with in situ micro-FTIR provides unambiguous evidence of burning in Stratum 10, including wood ash and bone, dated to ca. 1 million years ago (Berna et al. 2012). The location of the evidence of burning ca. 30 meters from the cave entrance makes it most likely that human activity is the explanation for fire in this context. It is significant that at Wonderwerk the traces of fire are associated with a low density of stone tools and faunal remains and that there are no clear combustion features (although this issue is the focus of renewed fieldwork at the site). The evidence from Wonderwerk makes it very difficult to sustain the argument that early hominins did not collect or maintain fire. However, the scarcity of evidence of fire in the early archaeological record and the nature of the archaeological context at Wonderwerk Cave are consistent with the possibility that early hominins did not maintain fire for long periods and that the way fire was used did not result in high archaeological visibility. Other claims for early use of fire include Cueva Negra, Spain (Walker et al. 2013), but beyond the presence of burning in association with lithics and fauna, the exposure at this site is too limited to provide evidence of how fire was used.

At present there is no archaeological basis for associating the dispersal of H. erectus with aspects of the maintenance or creation of fire by hominins (Hardy et al. 2017; Roebroeks and Villa 2011). We are left with the difficulty of reconciling the apparent evidence that suggests fire played a minor role in the early hominin record and the revolutionary impact of fire on early hominin adaptations proposed by Wrangham (2009). It is now essential to determine how the seasonal exploitation of collected fire might have offered an adaptive advantage, which, while more modest than the sweeping changes envisioned by Wrangham, was nonetheless significant.

One of the greatest hazards in the study of early human interactions with fire is the possibility that during some periods the activities related to the use of fire would have been spatially distinct from the activities that result in the accumulation of large assemblages of stone tools and faunal remains. If these activities were spatially distinct, then the likelihood of finding traces of fire, except in extraordinary contexts such as Wonderwerk Cave, becomes extremely low. Such a decoupling of lithic activity areas and the use of fire might offer a potential explanation for the absence of traces of fire on most early European archaeological localities.

The focus on a long prehistory of fire proposed here shifts the focus from simply identifying the earliest use of fire toward understanding the frequency and distribution of the use of fire. Sites lacking evidence for fire are thus as important as those with such traces preserved. From this perspective, the contrast between the low-density Acheulean occupation of Wonderwerk Cave (located on the eastern slopes of the Kuruman Hills) and the remarkably high density of occupation in the sites of the Kathu Complex on the western fringes of the Kuruman Hills is extremely significant (for the sites of the Kathu Complex, see Chazan et al. 2012; Matmon et al. 2015; Porat et al. 2009; Walker, Lukich, and Chazan 2014; Wilkins and Chazan 2012). The Acheulean and Fauresmith sites of the Kathu Complex comprise tens of millions of stone tools in stratigraphic contexts that rarely preserve bone (with the important exception of Kathu Pan 1) and do not preserve microstratigraphic evidence relevant to fire. However, in the massive collections of artifacts from these sites, burned artifacts are not evident based on macroscopic features such as pot lids and crazing, which makes it difficult to argue for the frequent use of fire at these localities. Wonderwerk Stratum 10 is significant not simply for the evidence of fire in and of itself but also within the broader context of fire use during the Acheulean. The presence of fire in a low-density cave site contemporaneous with the absence of fire on sites with massive accumulations of lithics suggests that during this time period, aspects of hominin behavior related to the use of fire and those related to the production and discard of large quantities of artifacts might have been somewhat spatially differentiated. Thus, a limitation of the archaeological record is that we are usually only able to identify the use of fire when evidence of burning is spatially associated with archaeological sites defined by the presence of detectable frequency of stone tools. The possibility of spatial decoupling of the use of fire and large-scale tool discard must be kept in mind when assessing the absence of evidence for the use of fire on most early sites. However, it nevertheless remains difficult to reconcile the spatial differentiation of the use of fire and the discard of tools with the pervasive role for fire in cooking envisioned by the cooking hypothesis.

Stage 2: Enhanced maintenance of fire was associated with the development of base camp sites. The maintenance of fire requires such occupation and there is strong evidence for the development of this behavior between 400,000 and 200,000 years ago.

Evidence from recent excavations at Schöningen, Beeches Pit, and Qesem Cave suggests that by 400,000 years ago hom-
inins had begun to collect and maintain fire (Karkanas et al. 2007; Preece et al. 2006; Stiner, Gopher, and Barkai 2010; Thieme 2005; although for Schöningen, see also Stahlsmith et al. 2015). The most compelling evidence comes from Qesem Cave, which is the only site with in situ micromorphological evidence of burning (Barkai et al. 2017; Karkanas et al. 2007). The lower component of Qesem Cave is primarily geogenic and preserves the remains of solitary hearths. The upper sequence follows a major rockfall and is primarily anthropogenic, consisting of a 4.5 meter thick ash-rich deposit. The lithic industry is blade dominated and attributed to the Amudian industry. Faunal analysis supports hunting of large game with hearth-based processing and sharing of meat (Stiner, Gopher, and Barkai 2010).

The evidence for the use of fire on archaeological sites intensifies around 200,000 years ago at the onset of the Middle Stone Age/Middle Paleolithic with sites with deep deposits of ash and charcoal and large quantities of burned bone and stone tools becoming a major component of the archaeological record (see, e.g., Meignen et al. 2009). The source of fire in these contexts has not been the subject of significant discussion, but I would set out as a proposition that the use of fire continued to be a seasonal aspect of adaptation based on the collection of fire rather than fire for technology for fire production. If it is true that these adaptations included the maintenance but not the creation of fire, there are a number of implications. The first of these is that evidence for fire should not be found on all sites but should be limited to those sites occupied during seasons of availability of natural sources of fire (and perhaps not annually). For example, in publications on the site of Holon, Israel, which is dated to ca. 200,000 years ago and contemporary with the later stages of the Qesem Cave sequence, Horwitz and I have pointed out the absence of any evidence of fire at this site, in marked contrast to Qesem (Chazan and Horwitz 2006; Horwitz and Chazan 2016).

If fire could only be collected but was becoming an increasingly critical aspect of hominin adaptation, this would also place a high degree of importance on the maintenance of fire. As a result there would be a degree of tethering of groups to places where fire was maintained in order to prolong the availability of this resource. The buildup of hearths at sites like Kebara Cave appears to be consistent with this kind of activity, as does the demonstration based on phytolith analysis that considerable quantities of wood and wood bark were brought onto sites as fuel (Albert et al. 1999, 2000, 2003). An adaptation based on the maintenance of seasonally collected fire would encourage the development of base camps and likely a division of labor such that some members of a group would remain on-site while others were engaged in hunting and gathering across the landscape. Isaac’s home base/food-sharing model built on the idea that there was a relationship between technology and social organization (Isaac 1978). As initially proposed by Roland (2004), the emergence of hearths as a central component of hominin occupation sites might be the context for the emergence of the home base/food-sharing model of hunter-gatherer society that Isaac (1984) attributed to the earliest toolmaking hominins.

It is important to emphasize that the knowledge and skill in the manipulation of fire during this stage was extremely sophisticated, as is indicated by the emerging indications that fire was used to transform materials, including lithics and resin (Brown et al. 2009; Koller et al. 2001; Pawlik and Thissen 2011). Although these techniques would enhance the role of fire, including for cooking, in hominin adaptation the reliance on fire as a seasonal resource would fall below the bar of year-round obligation cooking envisioned by the cooking hypothesis.

Stage 3: Enclosure of fire is a late development not associated with seasonal collection and maintenance (Sandgate et al. 2011). There appears to be an association between the enclosure of fire with habitual use of techniques to create fire. This stage in the scenario proposed here would provide the basis for an adaptation dependent on year-round obligation cooking.

Perhaps one of the oddest aspects of the archaeological record from the Middle Stone Age/Middle Paleolithic is the absence of constructed hearths, although in some cases, stones appear to have been pushed aside to clear an area (see Fernández Peris et al. 2010), and there is evidence of a stone-lined hearth at Qesem (see Shahack-Gross et al. 2014). As enclosure is seemingly cognitively underdemanding, there is a need to explain why this behavior did not develop for over 300,000 years of intensive hominin interaction with fire through collection and maintenance.

Similarly, there is no reason to question that early hominins had the dexterity or mental capacity needed to create fire. The abilities for early hominins to operate on the basis of complex concepts and with high degrees of skill are well established based on studies of stone tool technology. However, there is no inherent reason to assume that the dexterity used in lithic production would be transferred to the domain of producing fire simply because making fire would offer adaptive advantages.

Modern hunter-gatherers relied on friction to create embers that could then be coaxed into a flame. In his ethnography of the !Kung San, Richard Lee provides a good description of the use of a fire drill to make fire, a skill he reports all !Kung men and women still possessed at the time of his fieldwork. However, he emphasizes that this is a difficult technique and it was widely abandoned in favor of a flint and steel kit that could be purchased in trading stores (see also Friede 1978). It is worthwhile quoting Lee’s description of the use of the fire drill:

Two different kinds of wood are used: a hard wood such as Caetopraeces alexandri for the drill, and a softer wood such as Ricinodendron rautanenii (mongongo) for the base. The operator cuts a notch near the tip of the base stick held flat on the ground, with a knife blade to receive the coal, and places the tip of the drill stick in the notch. He twists the drill stick rapidly between his hands with a firm downward
pressure, taking care to keep the drill tip from slipping out of the notch. . . . Drilling fire looks deceptively easy in the hands of a skilled operator; yet real muscular strength and control are required to get the fire started. Even experts in the task are sweating with exertion after a minute’s drilling (Lee 1979:148).

Similar techniques have been documented using longitudinal friction in a trough to generate a spark (Perlès 1977; Rossotti 1993).

Since the survival of wooden artifacts in early hominin contexts is rare and, to date, no drilling sticks have been identified, we have no direct access to evidence of the initial creation of fire. However, we might be able to infer the presence of this technology if we assume that specific pervasive techniques (as opposed to generalized cognitive capacity) will be transferred across raw materials. Thus, for example, during the Lower Paleolithic percussion was applied to bone, apparently a transfer of a technique from lithics to bone (Gaudzinski et al. 2005). If drilling or grooving to create fire was an essential aspect of survival, it is reasonable to expect at least the occasional transfer of these motions to other materials.

Use wear on stone tools can provide a useful test for whether rotative action was part of the behavioral repertoire. Use wear analysis of Middle Paleolithic assemblages focuses on damage to the tips of tools due to use as weapons, and I have been unable to find explicit mention of use of tools as drills in the Middle Paleolithic. For example, in his analysis of use wear on points from Kebara Cave, Units IX–XII, Shea (1988) does not report evidence of drilling. However, Plisson and Beyries (1998) report that 25% of the tools studied from Stratum X and 6% of the tools from Stratum XI were used for *percuteur* from the illustration provided, it is not clear whether this corresponds to a rotative action (see Tringham et al. 1974, fig. 20) or whether this is an act of applying pressure without rotation. It is interesting that the assemblage from Umm el Tlel did not provide any evidence for the use of tools in this fashion (Plisson and Beyries 1998).

Currently there is little compelling evidence in the archaeological record before the later part of the Middle Stone Age and the early Upper Paleolithic for artifacts made using grooving or drilling. In the absence of such artifacts it would seem unlikely that hominin groups over this long time period consistently included individuals highly skilled in these techniques. There is an argument in the literature that fire could be created by striking flints against each other, resulting in a spark that could then cause ignition of tinder (Perlès 1977:33–34). Although there are many reports of using pyrite for this purpose (Sorensen, Roebroeks, and Van Gijn 2014; Stapert and Johansen 1999), and of course striking flint against metal was the basis for early firearms, it remains to be proven that the sparks created by striking flints create enough energy to cause ignition. Creating sparks through percussion might be significant for localized contexts where appropriate raw material is available but is not compelling as a general argument for fire in early hominin adaptation. At Wonderwerk there is a need to explore the possibility of creating fire by striking sparks off ironstone. In the Fauresmith of Wonderwerk there is evidence for incised lines on specularite, but it seems difficult to associate these shallow features with efforts to create fire (Watts, Wilkins, and Chazan 2016).

The emergence of rotative technologies and technologies involving grooving during the latter part of the Middle Stone Age and during the Upper Paleolithic make it plausible that during these periods hominins regularly created fire. It is interesting that in the Upper Paleolithic a range of methods also emerged for containing fire, including built hearths and portable lamps (on lamps, see de Beaune 1987; examples of built hearths include Leesch, Cattin, and Müller 2004, fig. 244; Leroi-Gourhan and Brézillon 1973, figs. 122 and 131; Movius 1977, pls. 27 and 53; for a discussion of containers, see Gamble 2007).

One possibility is that the adoption of built hearths was due to new functional demands (see March, Muhieddine, and Canot 2009), but it is also possible that the shift toward enclosing fire, and the linked shift toward creating fire, are related to a change in the conceptualization of fire. This is an abstract construct, but it draws on recent theoretical writing on the nature of artifacts that stresses that even chemical compounds—such as water—can take on the status of artifacts (Bloom 2007; Sperber 2007). It might be that what took place was a shift in the nature of the concept of fire, away from being purely a natural kind and toward hybridity. Paul Bloom makes a key distinction: “natural kinds [are] understood in terms of internal essences; artifacts are thought of in terms of considerations such as creator’s intent, characteristic function, and the social and cultural context of the artifact’s creation and use” (Bloom 2007:154). However, Bloom argues that in the process of concept formation and learning language children accept that some categories are understood as both artifact types and natural kinds. Could we conceive of the shift toward the production of fire as not only a change in technology, adaptation, and social structure but also a change in the conceptualization of the boundary between the natural and the artifact? Of course, the adoption of methods to regularly create fire would also have important implications not only for adaptation but also for social organization, notably in supporting increased mobility. It is interesting that the Upper Paleolithic is linked to the emergence of a specialized hunting tool kit that suggests emergence of hunting as a distinct sphere of activity in contrast to domestic activity (Chazan 2010; Tartar et al. 2005).

The Prehistory of Fire and Hominin Speciation

Correlating the scenario for the prehistory of fire presented here with hominin speciation events is challenging. In the cooking hypothesis (Wrangham 2009) the use of fire is connected to the first appearance of *Homo erectus*. The scenario presented here does not alter the possibility that the appearance of *H. erectus* was linked with a shift in hominin engagement with fire, although as noted above, the implications would not have been as...
far-reaching as envisioned by the cooking hypothesis. Stage 2 is presented here as a gradual process that develops during the period between 400,000 and 200,000 years ago. This would postdate the appearance of *Homo heidelbergensis*, if such a taxon has validity, but predate the first appearance of both Neanderthals and modern humans (for discussion of *H. heidelbergensis*, see Bräuer 2008; Stringer 2002). Stage 3 is also presented as a gradual process that is possibly precocious in Africa, where it occurred subsequent to the first appearance of modern humans. In Europe the appearance of stage 3 appears to correlate well with the Middle to Upper Paleolithic transition and the arrival of modern humans.

The important point here is precisely the lack of a direct correlation between speciation events in the hominin lineage and shifts in the relationship with fire, which fits with a conception of a give-and-take between innovation in hominin technology and aspects of biological evolution including speciation and dispersal. While mutations might have emerged that led to shifts in hominin behavior and/or cognition, it is also plausible that shifts in technology might have altered the selective advantage of traits already existing in populations, leading over time to changes in allele frequencies and ultimately to speciation. The concept of a long prehistory of fire moves away from viewing technology as an endowment made possible by favorable genetic mutations toward a more complex conception that looks at the interplay between genetics and culture in driving hominin evolutions.

Conclusion
The cooking hypothesis is a bold intervention in the study of human evolution. It is built on the idea of the origin of fire as a single unitary event. An alternative scenario is presented here, in which the use of fire, and by extension, reliance on cooked meat, was a process that extended over almost 2 million years. The developing interactions with fire played an integral role in shifting selective pressures. Changes in the interaction with fire were both a cause and a result of speciation and dispersal events. I have emphasized the multiple aspects of fire, particularly the relationships between society and technology. The adoption of a long prehistory of fire also provides a new perspective on criteria for acceptable evidence of early human use of fire, away from the particular case and toward synthesis of multiple lines of evidence.

In concluding, I would like to return to thinking about how early humans would have experienced fire. Fire remains a mysterious force, a mystery that is often drawn into religious ritual. Fire is a chemical reaction and escapes our normal experience of the tactile and real. While fire is extraordinary, it is also true that early humans were in regular interaction with the invisible. Hunting would require an understanding of the behavior of animals; collecting would have required similar knowledge of the processes through which plants grow and multiply. The simple act of making a stone tool involves the propagation of fracture, an act that irreversibly ruptures chemical bonds at a speed that cannot be measured. Fire is extraordinary, but early humans were familiar with the extraordinary and were adept at manipulating forces that cannot be seen and that modern science still struggles to understand. The use of fire is one aspect of the ability of early humans to control forces beyond comprehension—and from this perspective, the origins of fire is just one component of the ongoing process of human evolution.

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Identifying and Describing Pattern and Process in the Evolution of Hominin Use of Fire

by Dennis M. Sandgathe

Although research relating to Paleolithic fire use has a long history, it has seen a particular resurgence in the last decade. This has been fueled in part by improved analytical techniques, improved standards of data collection and reporting, and the discovery of new sites with important fire residues in Africa, the Middle East, and Europe. A major component of this new research has been to identify when “controlled use” and “habitual use” of fire developed among Pleistocene hominins. However, an important starting point of this discussion is defining what is meant by “controlled use” and “habitual use,” as these terms have come to be used in undefined, inconsistent ways in the literature. We also need to lay out clearly how these behaviors might be recognized in the archaeological record and come to some understanding of what the potential implications of the development of these technologies and their geographic and climatic contexts are for the course of hominin evolution.

Research into the early use of fire in prehistory has tended to focus on two major questions: when did hominins first begin using fire, and when did fire use become an integral component of hominin adaptations. Both of these questions tended to be dealt with in a rather simplistic manner in previous decades. This simplicity is not surprising for the early years of interest in prehistoric fire use, as researchers were only beginning to develop some understanding of the nature of the available data and the potential implications for fire use in early hominin adaptations. In recent years, we are starting to come to terms with how potentially long and complex the process of hominin development of pyrotechnology might have been. However, the current discussion often seems to continue to ignore the probable complexity of this development and how problematic the available evidence continues to be (with significant exceptions, e.g., Chazan 2017; Parker et al. 2016). This issue is reflected in the continued suggestion in some of the literature that there will be a single point in prehistory at which fire use was adopted by hominins and that from that point on it was used by all hominins everywhere (e.g., Barkai et al. 2017; Daniau, d’Errico, and Sanchez Goni 2011:1). It is becoming readily apparent that this scenario is a significant oversimplification of how the process probably occurred. While researchers do continue to look for the very earliest evidence for “controlled” use of fire (e.g., Berna et al. 2012), and this is surely an important question, a major hurdle in attempts to reach some understanding of the development of pyrotechnology continues to be a limited appreciation of the difficulty in distinguishing residues of hominin use of fire from naturally occurring fire, especially in Lower Pleistocene contexts (Barbetti 1986; see also the prelude in Goldberg, Miller, and Mentzer 2017). This is somewhat less of an issue with research in Middle Pleistocene contexts, where we do have some clear examples of hominin use of fire. In these cases, the goal appears to be more one of identifying examples of long-term, successive use of fire interpreted to be evidence of “habitual” fire use. So far, claims of habitual fire use are mainly only from single sites as opposed to examples of regional patterns of use (although see Roebroeks and Villa 2011). After the very earliest use, regular or successive use could be a reasonable expectation as the next major step in the development of hominin use of fire. However, what we mean by the terms “controlled” and “habitual” and what their implications for hominin evolution and adaptation are need to be discussed and better defined (e.g., Alperson-Afil 2017; Barkai et al. 2017). This requires the use of more explicit terminology and the development of a theoretical framework that better reflects the relationship between the evidence recovered from the archaeological record and our interpretations of it.

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Issues in Current Research on the Development of Pyrotechnology

Much has already been written on the issue of identifying the earliest evidence of hominin use of fire (e.g., Barbetti 1986; Bellomo 1993; Goudsblom 1986; Gowing et al. 1981; Gowlett and Wrangham 2013; James 1989; Pickering et al. 2008; Roe-
Another term has begun to become common: the use of fire with identifying the appearance of the fire. Other researchers are imagining the process of the development of fire and build on others 

(Goren-Inbar et al. 2004; James 1989) or the most commonly used in the literature in reference to the pre-Age of Fire (in speci

re use in the literature) probably appears quite early in the recent literature another term has begun to become common: “habitual use.” Both terms might be appropriate and useful in certain circumstances, but neither has been well defined so that other researchers understand what is meant or intended by their use. This makes it difficult for individuals to follow how other researchers are imagining the process of the development of fire use went, which makes it difficult to take into consideration and build on others’ work.

“Control of Fire” / “Controlled Use of Fire”?

Much of the research on early fire use has been concerned with identifying the appearance of the “controlled use of fire.” While the use of the term “control” (in specific reference to hominin fire use in the literature) probably appears quite early in Paleolithic archaeology, it becomes almost ubiquitous by the late 1970s and early 1980s (e.g., Bellomo 1994; Clark and Harris 1985; Goudsblom 1986; Gowlett et al. 1981; James [and comments] 1989; Rowlett 2000; and it would not be difficult to find 30 or 40 more references) and is the current term of choice in almost all the literature when referring to the early appearance of fire.

There are two important issues with the use of the term “control.” The first issue is that for many researchers there is no discussion of, or indication of, an expectation of potential stages in the development of fire use between when hominins were not using fire at all and their establishing control of it. This might be because for these researchers “control” means the most basic handling of fire, and so any potential evidence of early fire use is considered evidence for control of it (e.g., Alperson-Afil 2012, 2017; Alperson-Afil, Richter, and Goren-Inbar 2007; Bellomo 1993, 1994; Clark and Harris 1985; Goren-Inbar et al. 2004). (Some researchers use both “use” and “control” and seem explicitly to equate the terms, e.g., Bellomo [1993].) There are some important exceptions. A few researchers have made a distinction between “using” fire and “controlling” fire (Goren-Inbar et al. 2004; James 1989) or “opportunistic” (Shi melmitz et al. 2014) versus “controlled” (James 1989) use or “fortuitous use” versus control of fire (see also Bentsen 2014 and Goudsblom 1986 for discussions of the idea of stages of development of fire use). One exception is Pruetz and LaDuke (2010:4), who propose three cognitive and, presumably, chronologically successive stages that hominids would have to go through over the course of the development of fire use:

1. Conceptualization of fire: an understanding of the behavior of fire, which would allow activity in close proximity to it;
2. The ability to control a fire: the knowledge and ability to contain, feed, and extinguish fire;
3. The ability to start a fire: the knowledge and technology necessary to create fire at will.

A second exception is Smith (Monica L. Smith, personal communication, 2015), who proposed four stages, with very similar components, “that reflect increasing deliberation and control”: (1) habituation, (2) use, (3) curation, and (4) manufacture (see also Chazan 2017 for a similar discussion but slightly different criteria).

The second issue with the use of the term “control” is that while it is almost never explicitly defined or explained, for many researchers the apparent implication seems to be that control of fire meant hominins had the ability to create fire at will (Alperson-Afil 2008, 2012; Atwell, Kovarovic, and Kendal 2015; Brown 2009).

These distinctions are important considering the problems we often have in even identifying genuine anthropogenic fire residues in early sites (e.g., Shiøningen: Stahlschmidt et al. 2015; and Zhoukoudien: Goldberg et al. 2001). One of the frequent problems in developing an understanding of the development of pyrotechnology is achieving a reasonable degree of confidence that genuine fire residues identified at a site are actually anthropogenic and not the result of natural fires (this degree of confidence is, unfortunately, still a subjective thing and will vary between sites and researchers). For cave sites it has long been recognized that this is not nearly as big a problem (Berna et al. 2012; Roebroeks and Villa 2011), although there are obviously situations in which natural fire residues can occur in cave deposits (spontaneous combustion of organic deposits or sediments washing into a cave). For open-air sites, however, this must be seen as an important issue (see the prelude in Goldberg, Miller, and Mentzer 2017). In some regions and during some climatic periods, natural fires of various types (grass fires, brush fires, forest fires) are essentially ubiquitous, especially in the context of geological or Paleolithic timescales. This is particularly the case for consistently warmer and drier climatic regions such as Africa and southwest Asia and the huge span of time represented by the Lower Pleistocene. The probability seems vanishingly small that the location of any open-air Early Stone Age–Lower Paleolithic site would not have natural fires pass over it at least once (and probably many times) in the period of time since its deposition. If the site is not too deeply buried, artifacts and bones can be altered by the heat of a passing natural fire, and charcoal and ash from natural fires can be introduced
into the site sequence (see Aldeias 2017 and Aldeias et al. 2016 for a discussion of heat transfer into sediment substrates, and see Gowlett et al. 2017 for a study of the effects of natural fires on exposed objects).

Claims for early hominin use of fire are often based on arguments that the fire residues in question either bear no reasonable similarity to residues generally associated with natural fires (e.g., Bellomo 1993, 1994; Berna et al. 2012; Gowlett et al. 2005; Isaac 1982; James 1989; and Pickering et al. 2008) or the site deposits could not reasonably have been postdepositionally altered by natural fires (e.g., Alperson-Afil, Richter, and Goren-Inbar 2007; Goren-Inbar et al. 2004; Pickering et al. 2008). This might be a reasonable approach in some cases, but currently we still do not know enough about natural fires and their potential range of resulting residues—either types of residues, patterns of their dispersion, or how the heat of such fires may alter sediments and objects they come into contact with—to realistically make such arguments in many (perhaps most?) cases. Some experimental work has been done on this, but most of this has been very limited and has not gone far enough in bracketing the potential range of natural fire types, their residues, their effects on substrates (e.g., Aldeias 2017; Aldeias et al. 2012; Bellomo 1993; Canti and Linford 2000; Gowlett et al. 2017; March 1992). We do not know, for example, how frequently and in what circumstances a tree or bush burning down into its root system will result in patches of blackened or rubified sediments that look similar to the remains of an actual hearth. Or, as a further example, we do not have a good understanding at all of the relationship between variation in natural fire frequencies and resulting charcoal distributions and concentrations in regional sediment records (e.g., Peters and Higuera 2007). With respect to the issue of distinguishing residues of anthropogenic fire from natural fire, our interpretations have consistently been getting ahead of our understanding of the available data.

Therefore, in many cases we are still debating the origin of fire residues at archaeological sites, and so it is obviously problematic to start assuming that hominins created the fire. Even in cases where it seems very clear that the fires were the result of hominin behavior, there still remains the possibility that they acquired the fire from natural sources and did not create it themselves. This possibility seems to be consistently overlooked, underappreciated, or simply dismissed out of hand.

It seems logical to attempt to make some distinction between the different potential interpretations of the archaeological record. Depending on the nature of the available evidence and our confidence in it, we may arrive at one of the following general interpretations:

1. There are genuine fire residues associated with an archaeological site, but (at least currently) we have no way to determine confidently whether they are associated with hominin use of fire or are simply the result of natural fire and have no actual association with hominin behavior.

2. Fire residues identified at a site are demonstrably the result of hominins using fire, but we have no way to know how they acquired it (James’ [1989] and Goren-Inbar et al.’s [2004] “using fire” and Smith’s [personal communication, 2015] “use” of fire).

3. Hominins were using fire that they collected from a natural source (Shimelmitz et al.’s [2014] “opportunistic use” or James’ [1989] “fortuitous use”).

4. Hominins were using fire that they created with fire-making technology.

These reflect increasing levels of understanding of hominin behavior that, to achieve, would necessarily require increasingly better quality and types of data and increased confidence in our understanding of those data. I would suggest that for the majority of (perhaps all) claims of hominin use of fire associated with Middle Paleolithic–Middle Stone Age contexts and earlier, we are, at best, at the second level: fire residues identified at a site are demonstrably the result of hominins using fire, but we have no way to know how they acquired it. However, getting at some of these interpretations is going to be particularly difficult, for example, distinguishing hominin use of fire that they created from hominin use of fire collected from a natural source.

“Habitual” Use of Fire at Individual Sites

Much of the recent work on early fire has been focussed more on identifying Middle Pleistocene examples of repeated and continuous fire use at individual sites (e.g., Aldeias et al. 2012; Alperson-Afil 2008; Blasco et al. 2015; Karkanas et al. 2007; Shimelmitz et al. 2014). To date, the Lower Pleistocene record of hominin fire use is restricted entirely to Africa and southwest Asia and is best characterized in these regions as sketchy, to say the least. In light of this, the first appearances of examples of repeated fire use within a site rightly take on major significance in the history of development of pyrotechnology.

The oldest of these is the open-air site of Gesher Benot Ya’akov (Israel), dated to approximately 800 kya, which appears to have a few superimposed layers with fire residues (Alperson-Afil 2017). However, the earliest unquestionable examples of hominin use of fire and long-term, continuous fire use occur in cave sites in Israel dating from the latter half of the Middle Pleistocene. Between 350 and 200 kya we have the notable examples of Hayonim Cave, Qesem Cave, and Tabun Cave, where the sequences have recorded what appear to reflect regular and successive use of fire over much of this period. This record includes impressive examples of sequences of stacked hearths (on the order of dozens at Hayonim Cave; e.g., Bar Yosef et al. 2005; Goldberg and Bar-Yosef 1998; Shiegl et al. 1996) and notably high percentages of burned lithics in successive layers spanning tens of thousands of years in other cases (e.g., Tabun Cave; Shimelmitz et al. 2014). So far these sites appear to be the earliest evidence for fire use potentially
being a “regularly” repeated behavior and perhaps an integral component of a local population’s adaptation.

This long-term successive use of fire at individual sites has been described as the first evidence for “habitual” use (Bentsen 2014; Karkanas et al. 2007; Roebroeks and Villa 2011; Shahack-Gross et al. 2014; Shimelmitz et al. 2014). The term “habitual” has come into regular use in recent years. Shahack-Gross et al. (2014) define “habitual” (as they use it) as “systematically repeated use of fire in specific sites and/or regions” (12). Shimelmitz et al. (2014), in their observation of the fire record at Tabun, make a distinction between “occasional and opportunistic use of fire” and “habitual and planned” and suggest that “habitual” means that fire was “a consistent element in behavioral adaptations” (196). While it may very well be the case that different researchers intend different meanings when they use the term, “habitual use” typically means (or at least implies) “regular,” “successive,” or even “continuous,” or “perpetual.” In applying it to prehistoric fire use, would this mean daily use and at every occupation of a site by the hominins in question? It certainly seems to be strongly implied (though not explicitly stated) that at this level of use, hominins were making fire themselves and not relying on natural sources.

However, without some understanding of the actual frequency of fire use at these sites and whether these groups are actually creating fire at will, this becomes problematic. While at a coarse level the fire sequences may be described as “regular,” “successive,” or even “continuous,” there may still be decades, centuries, or in some cases even millennia between fire-use events. The types of data necessary to achieve the necessary resolution between fire events recorded in a site sequence can only potentially come from micromorphology, and even with this there are often going to be cases that are not definitive (see, e.g., Aldeais et al. 2012; Goldberg et al. 2012).

“Habitual” Use of Fire across a Region

Roebroeks and Villa (2011) take a broader geographical (continental) approach and discuss the evidence for the appearance of habitual use of fire in Europe. They make the case that increased frequencies of fire residues in Europe after 400 kya reflect the appearance of habitual use. The current evidence seems to show that any real use of fire only began after 400 kya (potential fire use at Cueva Negra is the single example that predates the late Middle Pleistocene; Walker et al. 2016). However, in higher latitudes—Europe in particular (although data from East and South Asia are very limited)—the evidence suggests that while some hominins in some places and at some times were definitely using fire, this use clearly remained intermittent and spotty even quite late in the Paleolithic. There is compelling evidence that as recently as the latter half of the Late Pleistocene, at least some hominin populations were not always using fire during significant occupations of cave sites (e.g., Aldeais et al. 2012; Dibble et al. 2017; Goldberg et al. 2012; Sandgathe et al. 2011a, 2011b). However, even in this context, the term “habitual” has come to be used to describe European hominin use of fire starting by 400 kya (Roebroeks and Villa 2011). It seems probable that in this case the term “habitual” has a different intended meaning.

But even if we were able to demonstrate that fire was being used at every visit to a particular site over very long periods or being used frequently across a region, this still does not necessarily imply that these hominins were creating the fire themselves. Examples of increased frequency or more regular use of fire at a site or in a region may just be reflecting regular access to natural fire sources in latitudes and climatic periods where the frequencies of natural fire are elevated—it may still be opportunistic use of natural fire (Sandgathe et al. 2011b) but in situations where the opportunity to access natural fire is frequent or even constant. Ultimately, our understanding of the development of pyrotechnology will need to rely even more heavily on the analysis of site-level data (sediments and residues; see Goldberg, Miller, and Mentzer 2017), but we also need to seriously consider any apparent geographic and temporal patterning of fire residues in the archaeological record.

Recognizing What the Patterns Mean

When it comes to interpreting the available data on Paleolithic fire use, of course we recognize that there are some general considerations. These include some basic taphonomic realities (see Aldeais 2017; Goldberg, Miller, and Mentzer 2017; Gowlett and Wrangham 2013 for more on this):

- A general loss of archaeological sites over time: the older the time period, the lower the percentage of sites that have been preserved because of simple geologic and erosional attrition.
- A loss of ephemeral fire residues over time: the greater the passage of time, the fewer the fire residues that tend to survive even in sites that have been preserved.
- Fire residues are likely to survive better in protected (cave) sites than in open-air sites. This is especially the case with ephemeral residues such as ash and charcoal and less so with residues such as burned bone or burned lichens.

The result is that there will be a general loss of evidence for fire in successively older sites. Because of this we must rely more heavily on types of evidence that are not typically affected by such taphonomic processes, for example, frequencies of burned flints, magnetic susceptibility, Fourier transform infrared spectroscopy, and micromorphological analysis (see Dibble et al. 2017; Goldberg, Miller, and Mentzer 2017).

There are also some important general considerations in not only the types of data but how the data should be compiled. For example, Gowlett and Wrangham (2013) correctly argue that the simple use of presence-absence data severely limits our potential understanding of early fire use. Simple presence-absence comparison of fire residues between different sites will not be particularly informative. For example, a single site with 10 stratigraphic layers, one of which has fire residues, will count
in the literature as a single example of positive evidence of fire use, while a site with 10 layers, none of which has fire residues, counts as a single example of lack of evidence of fire use. Such a scenario, with a total of 20 distinct strata potentially spanning many millennia only one of which has evidence for fire use, would be presented as 50% of the sites having evidence for fire. This was the approach that Roebroeks and Villa (2011) took. This is not intended as a criticism of their paper, as it was the first to even attempt to carry out broader regional analysis of fire-use patterns based on a large database, and they should be credited for this, but we are at the point where we should begin taking more sophisticated approaches to the available data.

It does seem to be the case that we are now developing an appreciation for the limitations of such basic presence-absence approaches, and there are some recent important exceptions where researchers have provided robust frequency data on fire residues or proxy fire data from individual sites. Two such examples (and undoubtedly there are others) are the recent work on evidence for fire use at Tabun (Shimelmitz et al. 2014) and many of the recent publications on the fire residues at Gesher Benot Ya’akov (Alperson-Afil 2008, 2017; Alperson-Afil, Richter, and Goren-Inbar 2007; Karkanas et al. 2007), where interpretation is based on quantifiable data that will arguably be very little affected by taphonomic processes (specifically, burned flints; see Aldeias 2017; Dibble et al. 2009, 2017; Sandgathe et al. 2011a). We would argue that our basic understanding of when and where fire was first used and when and where its use became regular is still, obviously, going to depend heavily on detecting the presence of early examples of clear anthropogenic fire use. What needs to be done is to use a more sophisticated version of what constitutes presence and absence along with the use of more quantitative data and analyses. We also need a more sophisticated understanding of what we might view as the “background noise” of natural fire residues that presumably make up the majority of fire residues in the larger depositional record of a region (although the fires being of natural origin does not preclude them being exploited by hominins).

We can, perhaps, suggest some general expectations about how the overall evidence might present. At least initial fire use was probably dependent on access to and exploitation of natural fire sources, which will typically be caused by lightning. Because temperature and humidity are the biggest factors in lightning frequencies, presence and absence and frequency of use were probably spatially and temporally dependent because access to natural fire was dependent on climate and environment. Therefore, until people developed fire-making techniques, the pattern was probably one of intermittent fire use depending, in large part, on the following.

• Latitude: we can expect to see initial, more frequent, and more regular fire use in warmer latitudes, where natural fire frequency was not (or was less) affected by global climate variability.

• Major climatic change: we can expect to see the gradual appearance of intermittent fire use at higher latitudes as hominins began to use fire more frequently, mainly corresponding to warm and wet climatic periods when natural fire was more readily available.

While much of the literature has presented arguments for evidence of “control of fire,” the current data on Paleolithic fire use may simply be a reflection of a reliance on natural fire sources, which would be dependent on lightning frequencies through time and across geographic space. For example, although hominins had been occupying higher, cooler latitudes in Europe and Asia since well before 1.0 mya, the very earliest potential evidence for fire use (claims dating from 1.6 mya to 800 kya) is in equatorial or subtropical latitudes (Africa and the Middle East), where lightning frequencies would have remained relatively high throughout the Pleistocene because these regions would not have been as affected by global climatic cycles as higher latitudes were (Fig. 1).

Assuming all the current claims for very early hominin use of fire in these regions are correct, the data still reflect a very spotty, intermittent record (e.g., Koobi Fora FxJj20 [Hlubik et al. 2017], Chesowanja in Kenya, Gadeb in Ethiopia, and Swartkrans and Wonderwerk Cave in South Africa). Furthermore, the first evidence of regionally based, repetitive or successive fire use is again restricted to subtropical latitudes beginning only between 800 and 400 kya (Gesher Benot Ya’akov, Tabun, Qesem, and Hayonim, all in Israel, and Cueva Negra in Spain). In latitudes above 35° north, the earliest potential evidence for any fire use is quite late, at ca. 400 kya (e.g., Beeches Pit in the United Kingdom, Bilzingsleben in Germany, and Vértesszöllös in Hungary). Even after fire does start appearing in Europe, the intermittent nature of the evidence throughout the late Middle and early Late Pleistocene shows strong patterns of correspondence to warmer climatic periods, which could still simply be reflecting a reliance on natural fire sources. These patterns are presented in Table 1, which is based on a limited literature review of evidence for fire in 377 stratigraphic levels from 52 Lower and Middle Paleolithic sites across Europe, with presence or absence of fire residues at all the components of these sites following Roebroeks and Villa’s (2011) qualitative criteria.

While these data must be viewed with caution (see table 1 notes), they appear to show three important things. The first is that there is currently a single site with potential evidence for hominin use of fire in Europe before marine isotope stage (MIS) 11, although we have clear evidence that hominins had arrived there before MIS 35 and potentially by MIS 45 (Carbonell et al. 2008; Moyano et al. 2011). The second is that aside from a complete lack of evidence from MIS 10 and 9, after this there is a general, though not entirely consistent, trend toward increasing frequency of fire residues. The third is that while there are examples of fire use in later cold periods, there appears to be a strong correlation between fire frequencies and warm periods. Taken at face value, this could be reflecting an ongoing reliance on natural fire sources. Intermittent fire use...
in Europe (beginning in the late Middle and continuing through early Middle Late Pleistocene) and examples of longer-term, successive fire use in southwest Asia starting in the Middle Pleistocene could be argued to be part of the same pattern: in both cases, hominins relying on natural fire that is predominantly a product of lightning frequency, which is strongly associated with warm climatic conditions. If fire-making techniques had been developed at this point and were widely employed, then there should be more examples in high-latitude regions with clear evidence for long-term, successive fire use. In fact, if hominins could make fire then, we might anticipate a strong positive correlation between fire residues and cold periods. The argument here is that an early, long-term reliance on natural fire sources is a very plausible explanation given the available data. The main point that should be taken from this is that even in the aggregate, the quality of our data and its potential to provide concrete interpretations are very limited and cannot necessarily be argued to be clear evidence for hominins having fire-making technology during these time periods. Currently the archaeological evidence does not support a scenario in which any hominins (in Europe, Asia, or Africa) were using fire regularly enough to suggest that it was an integral part of their adaptation until sometime in the Late Pleistocene. Neither does the current evidence support a scenario in which the existence of fire-making technology can be recognized or inferred until very late as well. The implication is that the actual process of the development of pyrotechnology was more complicated than has been presented in the literature so far. We are at the point where we need to move beyond the concept of a point in time where all hominins have "control" of fire, which eventually leads to fire use becoming "habitual" among all hominins. So, when it comes to evidence for fire use, how do we describe what we are finding in the archaeological record, and how do we describe our interpretations of it?

Figure 1. Location of the earliest sites (by region) with potential evidence for hominin fire use mapped onto the frequency distribution of lightning strikes today. In spite of the earliest appearance of hominins in different regions, the earliest evidence for fire use appears to follow a latitudinal pattern with the earliest sites located closer to the equator. The farther from the equator, the later the dates of the earliest sites with potential hominin fire use. This indicates that not only is there temporal patterning to the appearance of fire use, there is also a tentative geographic pattern that could be reflecting a reliance on natural fires, the frequency of which will have been strongly influenced by latitude. Darker areas indicate increased frequency of lightning strikes. Image modified from http://geology.com/articles/lightning-map.shtml).
A persistent topic in the symposium on which this supplemental issue of Current Anthropology is based was the nature of the various levels of analysis and interpretation inherent in trying to develop an understanding of the process of the development of hominin use of fire. However, any discussion is immediately limited by the lack of any established theoretical model(s) for such a process and a lack of common terms that researchers can use to explain their points of view. Such discussions are necessarily going to involve different categories of terminology depending on at what point we are in the research process. Specifically, we can identify three basic levels at which we might develop specific terminologies:

1. Describing archaeological phenomena: what terminology do we use to describe the actual residues of fire recovered from archaeological sites?
2. Interpretation of archaeological phenomena: what terminology do we use to describe in what specific context we think those residues were created? This would be site-specific behavior.
3. The theoretical process of development of hominin interaction with fire: what do we think is the broader behavioral context of the theoretical development of fire use in which these residues were created? This involves our interpretation of the role of fire in hominin adaptations.

Each of these levels already includes its own regularly used terms, and at least some of these are also problematic. For example, among archaeological phenomena and their interpretation, a commonly used term is “hearth,” which brings with it inherent implications that may or may not be supported by the actual fire residues identified at a site. The terms “control” and “habitual,” as they have generally been used in the literature, are examples of attempts to describe stages of hominin use of fire; that is, they relate mainly to the third category, the process of the development of hominin interaction with fire. These terms either need to be replaced or at least be better defined when they are used. I would argue for the former because both terms have already come to be so baggage laden.

### Describing the Theoretical Process of Development of Hominin Interaction with Fire

As discussed above, we can imagine a theoretical process of the development of the interaction between fire and people. Realistically, there had to have been a development of increasing complexity of hominin association with fire beginning from simple interaction with natural fire in the environment (a very common thing in grassland environments) to the eventual invention of fire-making technologies (Clark and Harris 1985; Pruetz and LaDuke 2010; Rolland 2004). Different researchers will undoubtedly have different ideas about the pace and temporal scale of this development and the interpretation of what it means in terms of hominin adaptation. We should also take care not to intentionally couch this development in terms of stages that imply directional progress or linear movement. However, we are realistically talking about levels of increased complexity. If individual “stages” in this in-
creasing complexity are not viewed as necessary preconditions for other stages, then we can avoid any implication of inherent linear progress. In some cases, hominin groups may potentially skip stages in the development of their use of fire that other hominins had gone through. However, practically speaking, it will probably be the case that in most (pre)historic circumstances there were common stages in the development of the use of fire.

Another very important part of this discussion is the recognition that the use of fire can be completely unrelated to the maintenance or manufacture of fire and could even involve no real control of fire. We can easily imagine such scenarios: hominins simply cooking a piece of meat over burning vegetation resulting from natural fire or, in an even less proximate interaction with fire, hominins intentionally foraging in burned-out areas shortly after a natural fire has passed (Herzog et al. 2014; Pruetz and LaDuke 2010).

The goal should be to use terms that express logical levels of increasing complexity or sophistication in the degree of interaction between hominins and fire. Starting at some point in the past before which hominins were not interacting with fire at all, they probably began some sort of simple interaction with fire, which may be as basic as the suppression of flight in face of natural fire (Clark and Harris 1985). This has been observed among chimpanzees (Pruetz and Herzog 2017; Pruetz and LaDuke 2010). This would logically be followed by simple use or application of fire, such as simply using fire for a task regardless of how complicated the task, where that use occurs, and how that fire was acquired. The example, given above, of hominins cooking food over naturally burning vegetation would represent this level of interaction. Presumably, at some point some hominins could begin to maintain fire regardless of its original source. This would involve adding fuel to vegetation that had been set on fire by a natural cause. Eventually hominins would have developed techniques for the actual manufacture and ignition of fire, creating fire where there was none. Based on this (and on the work of others such as Pruetz and LaDuke 2010 and Monica L. Smith, personal communication, 2015) we can suggest some concise, specific terminology that reflects these:

1. Habituation to natural fire,
2. Use of fire,
3. Maintenance of fire,
4. Manufacture of fire.

Over the long-term course of hominin evolution, there might have been a consistent or common sequence to the appearance of these levels of interaction with fire. While not implicit or necessary in all circumstances, logically, there is a certain degree of directionality to this list as presumably a hominin species had to become habituated to fire before it could achieve the other levels of interaction. Or, if it had the technology and know-how to manufacture fire, it had probably already spent some time using and maintaining fire. The use of fire has to have been a process like, for example, the development of lithic technologies.

We would not expect to see Solutrean points in an Oldowan assemblage. However, it is also the case that at some times and in some places, groups may not have followed this sequence. For example, for some groups, initial use and maintenance may have developed at more or less the same time.

This sequence does not necessarily have to have occurred just once in prehistory or at the same time and the same rate among different hominin populations. For some populations, simple use (with or without maintenance) may have been the limit of their fire use for very long periods of time before the ability to manufacture fire developed—if it did. In some regions (and time periods) high frequencies of natural fires may have provided some hominin groups with constant, reliable access to fire, limiting any pressure to develop fire-maintenance techniques or fire-manufacture technologies. In other regions, perhaps due to pressures resulting from low frequencies of natural fires or the importance of fire in exploiting certain resources, the development of fire-manufacture technology might occur very shortly after habituation. And in some regions and time periods, very low natural fire frequencies and a lack of fire-making technology could have meant that the use of fire was simply not an important part of some hominin populations’ adaptations (Henry 2017).

This terminology allows us to be interpretive about the archaeological record while avoiding unsupported presumptions (an issue that, I would argue, exists with the terms “control” and “habitual”). For example, depending on the specific details, we might be able to argue that fire residues in a hominin occupation are evidence of use and perhaps even maintenance, but the terminology makes it clear that in the event that there is no positive evidence that the hominins actually manufactured the fire, the interpretation ended there. We have the ability to deal with the strong disassociation between questions we might want to ask—could the hominins at this site make fire?—and our ability to answer them.

Conclusions

We do not yet have proper evidence to make big claims about either the earliest fire use or about when fire use became a regular component of technological repertoires and hominin adaptations came to depend on it. What is becoming clear is that our terminology, the approaches we take in our research, and the interpretations we arrive at from our analysis should start with some basic expectations about the course of the development of pyrotechnology.

- The development of pyrotechnology must be assumed to have been a long, drawn-out process that was probably relatively complex.
- Initial fire use was probably intermittent with frequent fits and starts, and this might have been the situation for a significant part of subsequent prehistory.
- Initial fire use was probably based on the exploitation of natural fire sources (mainly lightening-ignited vegetation
where and when available) and perhaps included simple fire maintenance at some times and in some places.

- Before the development and discovery of fire-making technology, it is unlikely that regular ("habitual") use of fire appeared among all hominins in all regions or even a single region at the same time—it probably became more regular in certain regions or with certain populations for periods of time.

- The discovery of fire-manufacturing technology probably occurred in multiple places and potentially even multiple times in any one region.

- Fire-manufacturing technology could well have been a relatively late development.

- Such technology may very well have been lost and rediscovered multiple times as well, either through group fissioning events or through local or regional extinction events of hominin populations.

- The evidence might suggest that fire had come to be used repeatedly and successively at a single site over a significant period of time, but this cannot be seen as de facto evidence for the regular, constant use by a population over an entire region, never mind a species.

The available data make it clear that before at least the Late Pleistocene, hominins are not using fire all the time. If the evidence suggests that frequent fire use among Middle Pleistocene European hominins (that is to say, high-latitude groups) does not appear before 400 kya, and these hominins were not using fire regularly (especially during cold periods), then this necessarily has implications for claims for any earlier fire use in Africa. If Lower and early Middle Pleistocene African hominins were using fire regularly (e.g., Tabun, Qesem) and knew how to create it, then at least some groups would presumably take this technology with them when they moved out of Africa into higher, cooler latitudes. The bottom line is that the evidence might be reflecting a much simpler scenario of fire-use development:

- Very intermittent and strictly opportunistic use of naturally available fire during the Lower and early Middle Pleistocene (e.g., Roebroeks and Villa 2011; Shimelmitz et al. 2014),

- More regular use of natural fire sources beginning in the latter half of the Middle Pleistocene—still mainly opportunistic exploitation of natural fire where and when it was regularly available—with perhaps the occasional (local?) development of fire-making technology.

We need more objective and general terms to allow us to describe these presumed increases in the complexity of hominin use of fire over time. Some of the very early associations of hominin occupations with fire residues in south and east Africa may simply reflect either the ubiquitous nature of natural fires in Africa or, perhaps, some level of habituation to (natural) fire. However, some of these hominin fire-residue associations might be the result of simple use of fire. Determining at what point hominins began fire maintenance becomes more problematic, and this is even more the case for manufacture of fire. Before we can seriously develop an understanding of the role of fire in hominin biocultural evolution and adaptation, we need a better understanding of the nature of these stages, including when and where they appeared and their subsequent durations.

A final note is that the development of fire-making techniques may also be dependent on biology and the emergence of hominin species with the requisite cognitive abilities. However, it should be stressed that fire making is a learned behavior (and, based on my own experience, very difficult to accomplish using traditional methods even if one knows theoretically exactly how to do it), and the lack of fire-making techniques is not an a priori indication of reduced cognitive abilities any more than a modern human society lacking computers would be.

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