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).

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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-
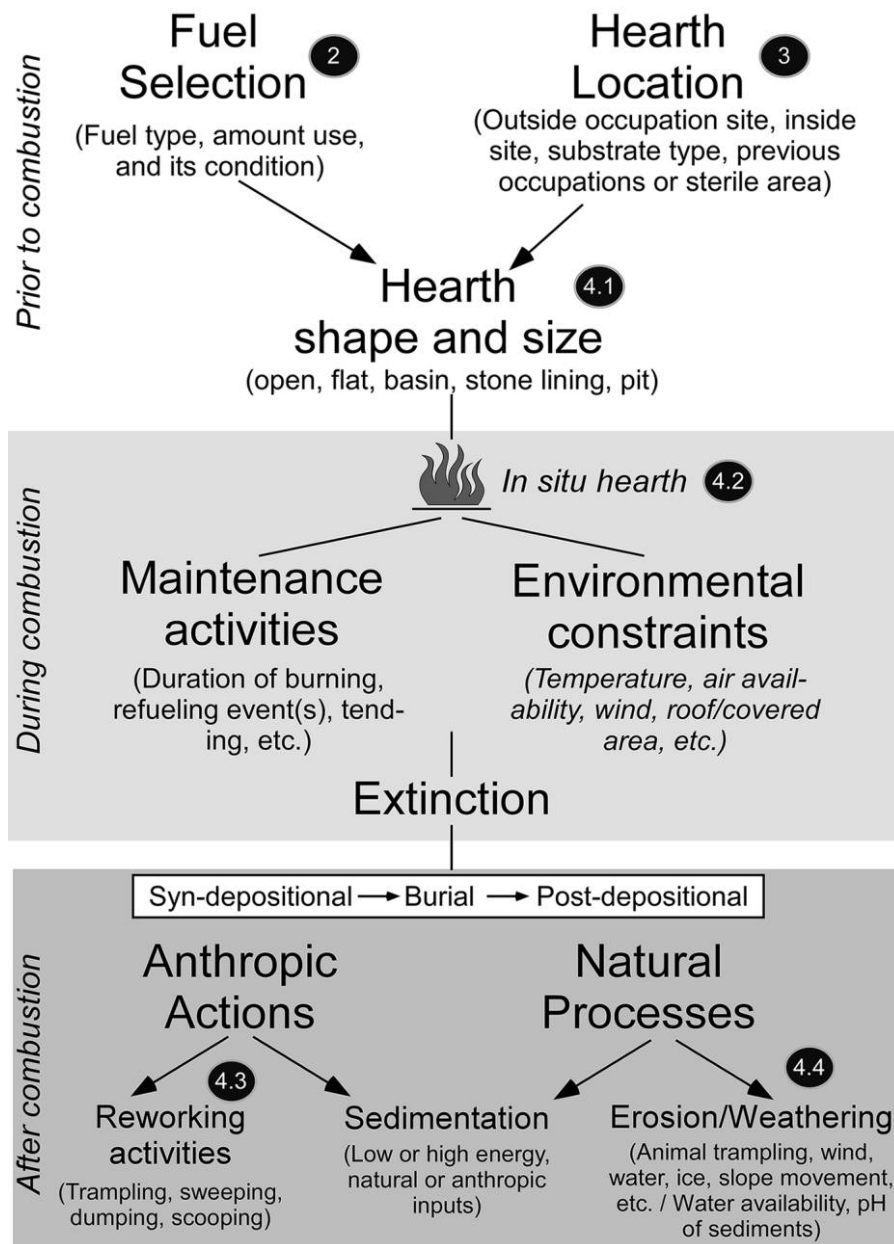

Figure 1. Schematic diagram illustrating the several phases of hearth construction, use, and preservation, with main factors influencing the archaeological expression of such evidence. The numbered circles refer to sections in this paper that deal with the available data from experimental archaeology. 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. 2016*a*, 2016*b*; 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 2002*a*, 2002*b*; Théry-Parisot, Chabal, and Chrzavzez 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 2002*a*, 2002*b*; 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, Úbeda, 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; Etiegni and Campbell 1991; March 1992; March et al. 2014; Théry-Parisot 2001; Théry-Parisot, Chabal, and Chrzavzez 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, Úbeda, 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 1. Fuel types and maximum temperatures recorded in experimental fires

Fuel type	Recorded temperature (°C)		Fire duration	Fire shape/dimensions	Fuel condition (moisture/state)	Study
	Maximum	Maximum mean				
Wood	900–1,000		NR	Open flat fires	NR	Stiner et al. 1995
Wood	995		4 days	Open flat fires	NR	Canti and Linford 2000
Wood	920		1 day	Open flat fires	NR	Canti and Linford 2000
Wood	892		4 days	Open flat fires	NR	Canti and Linford 2000
Wood	855		1 day	Open flat fires	NR	Canti and Linford 2000
Wood	818		1 day	Open flat fires	NR	Canti and Linford 2000
Wood		600	1–3 hours	Open flat fires		Bellomo 1993
Wood (sicklebush)	466, 760		3 hours 45 minutes, 5 hours	Open flat fires (ca. 40 cm diameter)	Wheel-dried (12%–20% moisture)	Bentsen 2013
Wood (sicklebush)	562, 730		4 hours 15 minutes, 5 hours	Open flat fires (ca. 40 cm diameter)	Wheel-dried (12%–20% moisture)	Bentsen 2013
Sedge (*Cyperus involucratus*)	>800		NR	Flat horizontally laid sedges	Sun-dried	Miller and Sievers 2012
Grass (*Themeda triandra* and *Imporada cylindrica*)		225		Flat horizontally laid sedges		Bellomo 1993
Grass (*Setaria plicatilis*)	157		NR	Open flat fires (30 cm × 30 cm)	Not fully dry	Miller and Sievers 2012
Bone (with some wood)		800–900	73–122 minutes	Slightly lowered, cleared surface (60 cm diameter)		Mentzer 2009
Bone (with some wood)		825–605		NR	Several (fresh and dry)	Théry-Parisot et al. 2005
Tree stump		250		NR		Bellomo 1993
Peat	800			NR	Air-dried for 1 month	Braadbaart et al. 2012
Cow dung	800			NR	Air-dried for 1 month	Braadbaart et al. 2012
Cattle and sheep dung	630			NR		Shahack-Gross et al. 2005

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, Schiegl 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. 2013*a*, 2013*b*; 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; Schiegl et al. 2003; Théry-Parisot 2002*a*) 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 et al. 2005), with a direct positive relationship between the amount of bone used and the longevity of flames in a fire (Théry-Parisot 2002*a*). 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 2002*a*; 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-Arieh 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 tis-

sues (which can include ash pseudomorphs), and residual inorganic components (Brochier 1983; Matthews 2010; Shahack-Gross 2011). Gur-Arieh 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
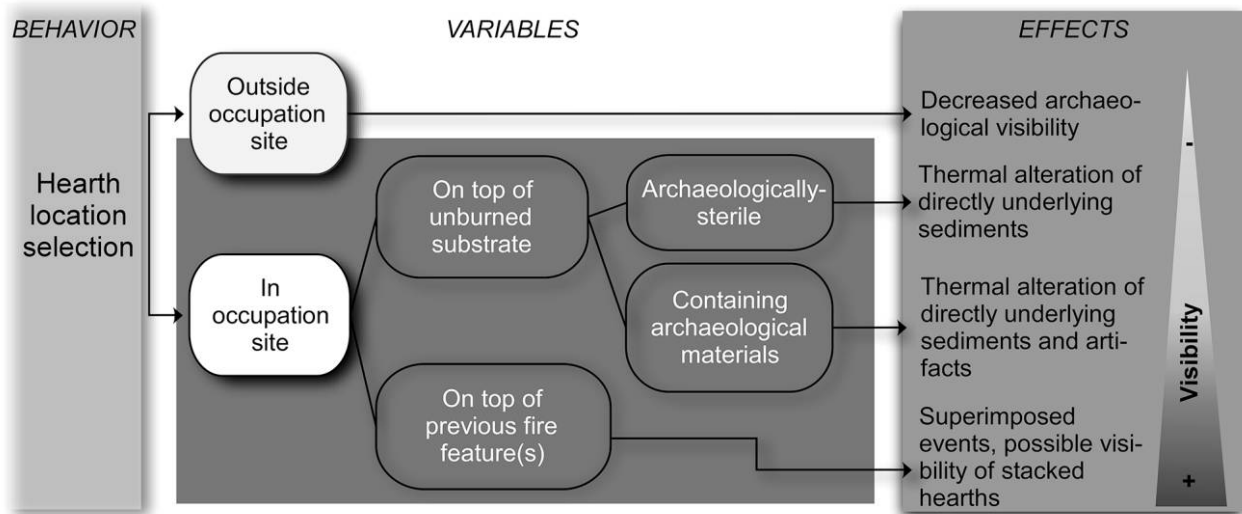
Figure 2. From the behavioral choice of hearth location to the summarized effects in terms of archaeological visibility. A color version of this figure is available online.

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. 2013*b*).

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. 2016*a*) 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. 2013*a*, 2013*b*; 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. 2013*b*; 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 taph-

onomic 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. 2016*a*), 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. 2016*a*). 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. 2016*a*; 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 over represented in archaeological contexts as the result of thermal modification of yellow ochre and iron-rich rocks buried underneath 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. 2016*a*), 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. (2013*a*) 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 rubefied 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. 2016*a*).

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 ex-

cavations (Mallol et al. 2013*a*, 2013*b*), 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. Undisturbed 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. 2013*a*, 2013*b*; March, Ferreri, and Guez 1993; March et al. 2014; Miller et al. 2010; Wattez 1996).

Extensive experimental work by March and colleagues (March 1992, 1996; March, Ferreri, and Guez 1993; March et al. 2014) has included research on different hearth shapes, namely simple, open horizontal fires and those constructed inside "cuvette" structures (i.e., shallow basin-shaped depressions). These experiments indicate that fires built inside a depression have a relatively high thermal efficiency when compared with flat open hearths. Cuvette fires tend to show uniform temperatures throughout a larger surface area and, because of incomplete and slower combustion, have a higher ratio of charcoal production compared with open horizontal features (March 1992; March et al. 2014). These differences seem to result from more controlled conditions of air circulation inside shallow depressions versus surface fires. Accordingly, the exposure to increased fluctuations in open ventilation conditions results in higher average temperatures in flat fires (see also Canti and Linford 2000), which, in turn, demands higher quantities of wood to keep a fire burning for a similar duration event. Interestingly, March et al. (2014) also observed that the substrates underlying cuvette fires may not show any signs of oxidation. This evidence is interpreted as resulting from the rapid infilling of the depression with combustion residues, namely ashes and charcoals, acting as thermal isolators and topographically raising the center of combustion (March et al. 2014). Such a hypothesis is in agreement with data on the thermal isolation effects of ashes reported by Canti and Linford (2000) and further tested experimentally by Aldeias et al. (2016*a*). Finally, variations in the diameter of open fires can be broadly correlated with the amount of fuel used, as shown in the experimental work of Bentsen (2012).

4.2. Alteration of Underlying Substrate

A hearth built on top of sedimentary substrates will result in some degree of thermal alteration of the material directly un-

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. 2013*a*; Miller and Sievers 2012; Sherwood and Chapman 2005). A small number of experiments provide a wider range of factors that allow for indepth generalizations about the type of modifications expected under certain conditions and, consequentially, what such alterations may mean for inferring past pyrogenic conditions.

One of the common thermally induced modifications is the development of a rubefied (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 rubefied 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 rubefication 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 rubefication.

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 underneath fires 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. (2013*a*), 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 residues 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 rubefication with the exception of heat applied to limestone sand and calcitic ashes (Aldeias et al. 2016*a*). In both of these cases, there were mineralogical and color changes associated with thermal alteration, but these did not assume the form of a rubefied 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 rubefied 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 rubefied substrate, when compared with a 6 cm thick rubefied layer using the same type of sediments but without organic matter (Aldeias et al. 2016*a*).

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. 2016*a*). This topography, readily visible in the case of rubefication, 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. (2016*b*) 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. (2013*b*) 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. 2013*b*; 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. 2013*b*; 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 diagenetic 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 overlying 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
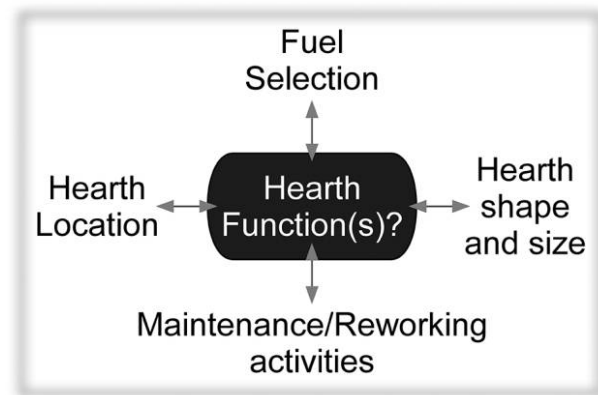

Figure 3. Graphical illustration of the potentially complex interplaying of variables for hearth function determination.

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. 2011*a*, 2011*b*). 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 evidence or are 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.

Acknowledgments

References Cited

Albert, R. M., M. K. Bamford, and D. Cabanes. 2006. Taphonomy of phytoliths and macroplants in different soils from Olduvai Gorge (Tanzania) and the application to Plio-Pleistocene palaeoanthropological samples. *Quaternary International* 148(1):78–94.

Albert, R. M., F. Berna, and P. Goldberg. 2012. Insights on Neanderthal fire use at Kebara Cave (Israel) through high resolution study of prehistoric combustion features: evidence from phytoliths and thin sections. *Quaternary International* 247(1):278–293.

Albert, R. M., and D. Cabanes. 2007. Fire in prehistory: an experimental approach to combustion processes and phytolith remains. *Israel Journal of Earth Sciences* 56(2–4):175–189.

Aldeias, V., P. Goldberg, D. Sandgathe, F. Berna, H. L. Dibble, S. P. McPherron, A. Turq, and Z. Rezek. 2012. Evidence for Neandertal use of fire at Roc de Marsal (France). *Journal of Archaeological Science* 39(7):2414–2423.

Aldeias, Vera, Harold L. Dibble, Dennis Sandgathe, Paul Goldberg, and Shannon J. P. McPherron. 2016*a*. How heat alters underlying deposits and implications for archaeological fire features: a controlled experiment. *Journal of Archaeological Science* 67:64–79.

Aldeias, Vera, Shira Gur-Arieh, Raquel Maria, Patricia Monteiro, and Pedro Cura. 2016*b*. Shell we cook it? an experimental approach to the microarchaeological record of shellfish roasting. *Archaeological and Anthropological Sciences*, doi:10.1007/s12520-016-0413-1.

Barkai, Ran, Jordi Rosell, Ruth Blasco, and Avi Gopher. 2017. Fire for a reason: barbecue at Middle Pleistocene Qesem Cave, Israel. *Current Anthropology* 58(suppl. 16):S314–S328.

Bellomo, R. V. 1993. A methodological approach for identifying archaeological evidence of fire resulting from human activities. *Journal of Archaeological Science* 20(5):525–553.

Bennett, J. L. 1999. Thermal alteration of buried bone. *Journal of Archaeological Science* 26(1):1–8.

Bentsen, Silje Evjenth. 2012. Size matters: preliminary results from an experimental approach to interpret Middle Stone Age hearths. *Quaternary International* 270:95–102.

———. 2013. Controlling the heat: an experimental approach to Middle Stone Age pyrotechnology. *South African Archaeological Bulletin* 68(198):137–145.

Beresford-Jones, D. G., K. Johnson, A. G. Pullen, A. J. E. Pryor, J. Svoboda, and M. K. Jones. 2010. Burning wood or burning bone? a reconsideration of flotation evidence from Upper Palaeolithic (Gravettian) sites in the Moravian Corridor. *Journal of Archaeological Science* 37(11):2799–2811.

Berna, F. 2010. Bone alteration and diagenesis. In *Scientific methods and cultural heritage: an introduction to the application of materials science to archaeometry and conservation science.* G. Artioli, ed. Pp. 364–367. Oxford: Oxford University Press.

Berna, F., and P. Goldberg. 2008. Assessing Paleolithic pyrotechnology and associated hominin behavior in Israel. *Israel Journal of Earth Sciences* 56: 107–121.

Berna, F., A. Matthews, and S. Weiner. 2004. Solubilities of bone mineral from archaeological sites: the recrystallization window. *Journal of Archaeological Science* 31(7):867–882.

Berna, Francesco, Adi Behar, Ruth Shahack-Gross, John Berg, Elisabetta Boaretto, Ayelet Gilboa, Ilan Sharon, et al. 2007. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age strata at Tel Dor (Israel). *Journal of Archaeological Science* 34 (3):358–373.

Braadbaart, Freek, and Imogen Poole. 2008. Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. *Journal of Archaeological Science* 35(9):2434–2445.

Braadbaart, Freek, Imogen Poole, Hans D. J. Huisman, and Bertil van Os. 2012. Fuel, fire and heat: an experimental approach to highlight the potential of studying ash and char remains from archaeological contexts. *Journal of Archaeological Science* 39(4):836–847.

Brochier, Jacques E. 1983. Combustion et parcage des herbivores domestiques: le point de vue du sédimentologue. *Bulletin de la Société Préhistorique Française: Comptes Rendus des Séances Mensuelles Paris* 80(5):143–145.

———. 1996. Feuilles ou fumiers? observations sur le rôle des poussières sphérolitiques dans l'interprétation des dépôts archéologiques holocènes. *Anthropozoologica* 24:19–30.

Brodard, Aurélie, Delphine Lacanette-Puyo, Pierre Guibert, François Lévêque, Albane Burens, and Laurent Carozza. 2015. A new process of reconstructing archaeological fires from their impact on sediment: a coupled experimental and numerical approach based on the case study of hearths from the cave of Les Fraux (Dordogne, France). *Archaeological and Anthropological Sciences*, doi:10.1007/s12520-015-0250-7.

Brown, Kyle S., Curtis W. Marean, Andy I. R. Herries, Zenobia Jacobs, Chantal Tribolo, David Braun, David L. Roberts, Michael C. Meyer, and Jocelyn Bernatchez. 2009. Fire as an engineering tool of early modern humans. *Science* 325(5942):859–862.

Buenger, Brent A. 2003. The impact of wildland and prescribed fire on archaeological resources. PhD dissertation, University of Kansas, Lawrence.

Cabanes, D., S. Weiner, and R. Shahack-Gross. 2011. Stability of phytoliths in the archaeological record: a dissolution study of modern and fossil phytoliths. *Journal of Archaeological Science* 38(9):2480–2490.

Cain, Chester R. 2005. Using burned animal bone to look at Middle Stone Age occupation and behavior. *Journal of Archaeological Science* 32(6):873–884.

Camarós, E., M. Cueto, L. Teira, Susanne C. Münzel, F. Plassard, P. Arias, and F. Rivals. Forthcoming. Bears in the scene: Pleistocene complex interactions with implications concerning the study of Neanderthal behavior. *Quaternary International.* http://dx.doi.org/10.1016/j.quaint.2015.11.027.

Campbell, G. S., J. D. Jungbauer Jr., K. L. Bristow, and R. D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. *Soil Science* 159 (6):363–374.

Canti, M. 1998. Origin of calcium carbonate granules found in buried soils and Quaternary deposits. *Boreas* 27(4):275–288.

———. 2003. Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. *Catena* 54(3):339–361.

Canti, M. G., and N. Linford. 2000. The effects of fire on archaeological soils and sediments: temperature and colour relationships. *Proceedings of the Prehistoric Society* 66:385–395.

Chu, Vikki, Lior Regev, Steve Weiner, and Elisabetta Boaretto. 2008. Differentiating between anthropogenic calcite in plaster, ash and natural calcite using infrared spectroscopy: implications in archaeology. *Journal of Archaeological Science* 35(4):905–911.

Cohen-Ofri, I., L. Weiner, E. Boaretto, G. Mintz, and S. Weiner. 2006. Modern and fossil charcoal: aspects of structure and diagenesis. *Journal of Archaeological Science* 33(3):428–439.

Costamagno, S., I. Théry-Parisot, J. P. Brugal, and R. Guilbert. 2005. Taphonomic consequences of the use of bones as fuel: experimental data and

archaeological applications. In *Biosphere to lithosphere: new studies in vertebrate taphonomy.* T. O'Connor, ed. Pp. 51–62. London: Oxbow.

Courty, M. A., E. Carbonell, J. Vallverdú Poch, and R. Banerjee. 2012. Microstratigraphic and multi-analytical evidence for advanced Neanderthal pyrotechnology at Abric Romaní (Capellades, Spain). *Quaternary International* 247(1):294–312.

Dibble, Harold L., Aylar Abodolahzadeh, Vera Aldeias, Paul Goldberg, Shannon P. McPherron, and Dennis M. Sandgathe. 2017. How did hominins adapt to Ice Age Europe without fire? *Current Anthropology* 58(suppl. 16): S278–S287.

Dibble, Harold L., Francesco Berna, Paul Goldberg, Shannon P. McPherron, Susan Mentzer, Laura Niven, Daniel Richter, Dennis Sandgathe, Isabelle Théry-Parisot, and Alan Turq. 2009. A preliminary report on Pech de l'Azé IV, Layer 8 (Middle Paleolithic, France). *PaleoAnthropology* 2009:182–219, doi:10.4207/PA.2009.ART30.

Elbaum, Rivka, Steve Weiner, Rosa M. Albert, and Michael Elbaum. 2003. Detection of burning of plant materials in the archaeological record by changes in the refractive indices of siliceous phytoliths. *Journal of Archaeological Science* 30(2):217–226.

Etiegni, L., and A. G. Campbell. 1991. Physical and chemical characteristics of wood ash. *Bioresource Technology* 37(2):173–178.

Gabucio, Maria Joana, Isabel Cáceres, Jordi Rosell, Palmira Saladié, and Josep Vallverdú. 2014. From small bone fragments to Neanderthal activity areas: the case of Level O of the Abric Romaní (Capellades, Barcelona, Spain). *Quaternary International* 330:36–51.

Godino, Ivan Briz, Myrian Álvarez, Andrea Balbo, Débora Zurro, Marco Madella, Ximena Villagrán, and Charles French. 2011. Towards high-resolution shell midden archaeology: experimental and ethnoarchaeology in Tierra del Fuego (Argentina). *Quaternary International* 239:125–134.

Goldberg, P., H. Dibble, F. Berna, D. Sandgathe, S. J. P. McPherron, and A. Turq. 2012. New evidence on Neandertal use of fire: examples from Roc de Marsal and Pech de l'Azé IV. *Quaternary International* 247:325–340.

Goldberg, Paul, Christopher E. Miller, and Susan M. Mentzer. 2017. Recognizing fire in the Paleolithic archaeological record. *Current Anthropology* 58(suppl. 16):S175–S190.

Gonçalves, D., T. J. U. Thompson, and E. Cunha. 2011. Implications of heat-induced changes in bone on the interpretation of funerary behaviour and practice. *Journal of Archaeological Science* 38(6):1308–1313.

Gowlett, J. A. J. 2006. The early settlement of northern Europe: fire history in the context of climate change and the social brain. *Comtes Rendu Palevol* 5: 299–310.

Gowlett, J. A. J., J. S. Brink, Adam Caris, Sally Hoare, and S. M. Rucina. 2017. Evidence of burning from bushfires in southern and east Africa and its relevance to hominin evolution. *Current Anthropology* 58(suppl. 16):S206–S216.

Gur-Arieh, S., E. Mintz, E. Boaretto, and R. Shahack-Gross. 2013. An ethnoarchaeological study of cooking installations in rural Uzbekistan: development of a new method for identification of fuel sources. *Journal of Archaeological Science* 40(12):4331–4347.

Gur-Arieh, Shira, Ruth Shahack-Gross, Aren M. Maeir, Gunnar Lehmann, Louise A. Hitchcock, and Elisabetta Boaretto. 2014. The taphonomy and preservation of wood and dung ashes found in archaeological cooking installations: case studies from Iron Age Israel. *Journal of Archaeological Science* 46:50–67.

Henry, Amanda G. 2017. Neanderthal cooking and the costs of fire. *Current Anthropology* 58(suppl. 16):S329–S336.

Henry, Auréade, and Isabelle Théry-Parisot. 2014. From Evenk campfires to prehistoric hearths: charcoal analysis as a tool for identifying the use of rotten wood as fuel. *Journal of Archaeological Science* 52:321–336.

Huisman, D. J., F. Braadbaart, I. M. van Wijk, and B. J. H. van Os. 2012. Ashes to ashes, charcoal to dust: micromorphological evidence for ash-induced disintegration of charcoal in Early Neolithic (LBK) soil features in Elsloo (The Netherlands). *Journal of Archaeological Science* 39(4):994–1004.

James, Steven, R. W. Dennell, Allan S. Gilbert, Henry T. Lewis, J. A. J. Gowlett, Thomas F. Lynch, W. C. McGrew, et al. 1989. Hominid use of fire in the Lower and Middle Pleistocene. *Current Anthropology* 30(1):1–26.

Joly, D., and R. March. 2003. Étude des ossements brûlés: nouvelles méthodes pour la détermination des températures. In *Le feu domestique et ses structures au néolithique et aux âges des métaux: actes du colloque de Bourg-en-Bresse et Beaune, 7 et 8 octobre 2000.* Montagnac: M. Mergoil.

Karkanas, P. 2010. Preservation of anthropogenic materials under different geochemical processes: a mineralogical approach. *Quaternary International* 214:63–69.

Karkanas, P., O. Bar-Yosef, P. Goldberg, and S. Weiner. 2000. Diagenesis in prehistoric caves: the use of minerals that form in situ to assess the completeness of the archaeological record. *Journal of Archaeological Science* 27 (10):915–929.

Karkanas, P., R. Shahack-Gross, A. Ayalon, M. Bar-Matthews, R. Barkai, A. Frumkin, A. Gopher, and M. C. Stiner. 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution* 53(2):197–212.

Laloy, J. 1981. *Recherche d'une méthode pour l'exploitation des témoins de combustion*. Paris: Centre de Recherches Préhistoriques, Cahiers.

Maki, David, Jeffrey A. Homburg, and Scott D. Brosowske. 2006. Thermally activated mineralogical transformations in archaeological hearths: inversion from maghemite γFe2O4 phase to haematite αFe2O4 form. *Archaeological Prospection* 13(3):207–227.

Mallol, C., C. M. Hernández, D. Cabanes, A. Sistiaga, J. Machado, T. Rodríguez, L. Pérez, and B. Galván. 2013a. The black layer of Middle Palaeolithic combustion structures: interpretation and archaeostratigraphic implications. *Journal of Archaeological Science* 40(5):2515–2537.

Mallol, C., F. W. Marlowe, B. M. Wood, and C. C. Porter. 2007. Earth, wind, and fire: ethnoarchaeological signals of Hadza fires. *Journal of Archaeological Science* 34(12):2035–2052.

Mallol, Carolina, Cristo M. Hernández, Dan Cabanes, Jorge Machado, Ainara Sistiaga, Leopoldo Pérez, and Bertila Galván. 2013b. Human actions performed on simple combustion structures: an experimental approach to the study of Middle Palaeolithic fire. *Quaternary International* 315:3–15.

March, R. J., J. C. Ferreri, and C. Guez. 1993. Étude des foyers préhistoriques des gisements Magdaléniens du Bassin parisien: l'approche expérimentale. *Mémoires du Groupement Archéologique de Seine-et-Marne* (1):87–95.

March, R. J., and G. Wunsch. 2003. Loupes et lentilles obscures: à propos de la fonction des structures de combustion. In *Le feu domestique et ses structures au néolithique et aux âges des métaux: actes du colloque de Bourg-en-Bresse et Beaune, 7 et 8 octobre 2000*. Montagnac: M. Mergoil.

March, Ramiro J. 1992. L'utilisation du bois dans les foyers préhistoriques: une approche expérimentale. *Bulletin de la Societé Botanique Française: Actualités Botaniques* 139(2–4):245–253, doi:10.1080/01811789.1992.10827103.

———. 2013. Searching for the functions of fire structures in Eynan (Mallaha) and their formation processes: a geochemical approach. In *Natufian foragers in the Levant: terminal Pleistocene social changes in western Asia*. Ofer Bar-Yosef and François R. Valla, eds. Ann Arbor, MI: International Monographs in Prehistory.

March, Ramiro Javier. 1996. L'Etude des structures de combustion préhistoriques: une approche interdisciplinaire. In *XIII International Congress of Prehistoric and Protohistoric Sciences*. O. Bar Yosef, L. Cavalli-Sforza, R. J. March, and D. R. Piperno, ed. Forli-Italia-8/14, pp. 251–275.

March, Ramiro Javier, Alexandre Lucquin, Delphine Joly, Juan Carlos Ferreri, and Mohamad Muhieddine. 2014. Processes of formation and alteration of archaeological fire structures: complexity viewed in the light of experimental approaches. *Journal of Archaeological Method and Theory* 21(1):1–45.

Marquer, L., T. Otto, R. Nespoulet, and L. Chiotti. 2010. A new approach to study the fuel used in hearths by hunter-gatherers at the Upper Palaeolithic site of Abri Pataud (Dordogne, France). *Journal of Archaeological Science* 37(11):2735–2746.

Matthews, W. 2010. Geoarchaeology and taphonomy of plant remains and microarchaeological residues in early urban environments in the Ancient Near East. *Quaternary International* 214(1/2):98–113.

Mazza, Paul Peter Anthony, Fabio Martini, Benedetto Sala, Maurizio Magi, Maria Perla Colombini, Gianna Giachi, Francesco Landucci, Cristina Lemorini, Francesca Modugno, and Erika Ribechini. 2006. A new Palaeolithic discovery: tar-hafted stone tools in a European Mid-Pleistocene bone-bearing bed. *Journal of Archaeological Science* 33(9):1310–1318.

Meignen, L., P. Goldberg, and O. Bar-Yosef. 2007. The hearths at Kebara Cave and their role in site formation processes. In *Kebara Cave Mt. Carmel, Israel: the middle and upper Paleolithic archaeology*, pt. 1. O. Bar-Yosef and L. Meignen, eds. Pp. 91–122. Cambridge, MA: Peabody Museum of Archaeology and Ethnology, Harvard University.

Meignen, Liliane, Paul Goldberg, and Ofer Bar-Yosef. 2014. Together in the field: interdisciplinary work in Kebara and Hayonim caves (Israel). *Archaeological and Anthropological Sciences*, doi:10.1007/s12520-014-0185-4.

Mentzer, Susan M. 2009. Bone as a fuel source: the effects of initial fragment size distribution. In *Gestion des combustibles au Paleolithique et au Mesolithique: nouveaux outiles, nouvelles interpretations*. Isabelle Théry-Parisot,

Sandrine Costamagno, and Auréade Henry, eds. Pp. 53–64. Oxford: Archaeopress.

———. 2014. Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory* 21(3):616–668.

Miller, Christopher E., N. Conard, P. Goldberg, and F. Berna. 2010. Dumping, sweeping, and trampling: experimental micromorphological analysis of anthropogenically modified combustion features. *Palethnology* 2:25–37.

Miller, Christopher E., and Christine Sievers. 2012. An experimental micromorphological investigation of bedding construction in the Middle Stone Age of Sibudu, South Africa. *Journal of Archaeological Science* 39(10):3039–3051.

Morin, Eugène. 2010. Taphonomic implications of the use of bone as fuel. *Palethnology* 2:209–217.

Nicholson, Rebecca A. 1992. Bone survival: the effects of sedimentary abrasion and trampling on fresh and cooked bone. *International Journal of Osteoarchaeology* 2(1):79–90.

Pereira, Paulo, Xavier Úbeda, and Deborah A. Martin. 2012. Fire severity effects on ash chemical composition and water-extractable elements. *Geoderma* 191:105–114.

Piperno, D. R., D. M. Pearsall, R. A. Benfer Jr., L. Kealhofer, Z. Zhao, and Q. Jiang. 1999. Phytolith morphology. *Science* 283(5406):1265–1266.

Roebroeks, W., and P. Villa. 2011. On the earliest evidence for habitual use of fire in Europe. *Proceedings of the National Academy of Sciences of the USA* 108(13):5209–5214.

Sandgathe, Dennis M., Harold L. Dibble, Paul Goldberg, Shannon P. McPherron, Alain Turq, L. Niven, and J. Hodgkins. 2011a. Timing of the appearance of habitual fire use. *Proceedings of the National Academy of Sciences of the USA* 108(29), doi:10.1073/pnas.1106759108.

———. 2011b. On the role of fire in Neandertal adaptations in western Europe: evidence from Pech de l'Azé and Roc de Marsal, France. *PaleoAnthropology* 2011:216–242.

Schiegl, S., P. Goldberg, O. Bar-Yosef, and S. Weiner. 1996. Ash deposits in Hayonim and Kebara caves, Israel: macroscopic, microscopic and mineralogical observations, and their archaeological implications. *Journal of Archaeological Science* 23(5):763–781.

Schiegl, S., P. Goldberg, H. U. Pfretzschner, and N. J. Conard. 2003. Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between in situ fireplaces and dumping areas. *Geoarchaeology* 18(5):541–565.

Schiegl, Solveig, Simcha Lev-Yadun, Ofer Bar-Yosef, Ahmed El Goresy, and Stephen Weiner. 1994. Siliceous aggregates from prehistoric wood ash: a major component of sediments in Kebara and Hayonim caves (Israel). *Israel Journal of Earth Sciences* 43(3/4):267–278.

Schmidt, Patrick. 2013. *Le traitement thermique des matières lithiques: que se passe-t-il lors de la chauffe?*. BAR International Series 2470. Oxford: Archaeopress.

Schmidt, Patrick, Guillaume Porraz, Aneta Slodczyk, Ludovic Bellot-Gurlet, William Archer, and Christopher E. Miller. 2013. Heat treatment in the South African Middle Stone Age: temperature induced transformations of silcrete and their technological implications. *Journal of Archaeological Science* 40(9):3519–3531.

Sergant, J., P. Crombé, and Y. Perdaen. 2006. The "invisible" hearths: a contribution to the discernment of Mesolithic non-structured surface hearths. *Journal of Archaeological Science* 33(7):999–1007.

Shahack-Gross, R., F. Berna, P. Karkanas, C. Lemorini, A. Gopher, and R. Barkai. 2014. Evidence for the repeated use of a central hearth at Middle Pleistocene (300 ky ago) Qesem Cave, Israel. *Journal of Archaeological Science* 44:12–21.

Shahack-Gross, R., and I. Finkelstein. 2008. Subsistence practices in an arid environment: a geoarchaeological investigation in an Iron Age site, the Negev Highlands, Israel. *Journal of Archaeological Science* 35(4):965–982.

Shahack-Gross, Ruth. 2011. Herbivorous livestock dung: formation, taphonomy, methods for identification, and archaeological significance. *Journal of Archaeological Science* 38(2):205–218.

Sherwood, Sarah C., and Jefferson Chapman. 2005. The identification and potential significance of Early Holocene prepared clay surfaces: examples from Dust Cave and Icehouse Bottom. *Southeastern Archaeology* 24(1):70–82.

Sievers, C., and L. Wadley. 2008. Going underground: experimental carbonization of fruiting structures under hearths. *Journal of Archaeological Science* 35(11):2909–2917.

Simpson, Ian A., Orri Vésteinsson, W. Paul Adderley, and Thomas H. McGovern. 2003. Fuel resource utilisation in landscapes of settlement. *Journal of Archaeological Science* 30(11):1401–1420.

Stahlschmidt, Mareike C., Christopher E. Miller, Bertrand Ligouis, Ulrich Hambach, Paul Goldberg, Francesco Berna, Daniel Richter, Brigitte Urban, Jordi Serangeli, and Nicholas J. Conard. 2015. On the evidence for human use and control of fire at Schöningen. *Journal of Human Evolution* 89:181–201.

Stiner, M. C., S. L. Kuhn, S. Weiner, and O. Bar-Yosef. 1995. Differential burning, recrystallization, and fragmentation of archaeological bone. *Journal of Archaeological Science* 22(2):223–237.

Théry, I., J. Gril, J. L. Vernet, L. Meignen, and J. Maury. 1996. Coal used for fuel at two prehistoric sites in southern France: Les Canalettes (Mousterian) and Les Usclades (Mesolithic). *Journal of Archaeological Science* 23(4):509–512.

Théry-Parisot, I., L. Chabal, and J. Chrzavzez. 2010. Anthracology and taphonomy, from wood gathering to charcoal analysis: a review of the taphonomic processes modifying charcoal assemblages, in archaeological contexts. *Palaeogeography, Palaeoclimatology, Palaeoecology* 291(1/2):142–153.

Théry-Parisot, I., and A. Henry. 2012. Seasoned or green? radial cracks analysis as a method for identifying the use of green wood as fuel in archaeological charcoal. *Journal of Archaeological Science* 39(2):381–388.

Théry-Parisot, Isabelle. 2001. *Economie des combustibles au paléolithique: expérimentation, taphonomie, anthracologie.* Paris: CNRS.

———. 2002*a.* Fuel management (bone and wood) during the lower Aurignacian in the Pataud rock shelter (Lower Palaeolithic, Les Eyzies de Tayac, Dordogne, France): contribution of experimentation. *Journal of Archaeological Science* 29(12):1415–1421.

———. 2002*b.* Gathering of firewood during the Palaeolithic. *Bar International Series* 1063:243–250.

Théry-Parisot, Isabelle, and Sandrine Costamagno. 2005. Propriétés combustibles des ossements. *Gallia Préhistoire* 47:235–254.

Théry-Parisot, Isabelle, Sandrine Costamagno, Jean-Philip Brugal, Philippe Fosse, and Raphaële Guilbert. 2005. The use of bone as fuel during the Palaeolithic: experimental study of bone combustible properties. In *The zooarchaeology of fats, oils, milk, and dairying.* J. Mulville and A. Outram, eds. Oxford: Oxbow.

Toffolo, Michael B., and Elisabetta Boaretto. 2014. Nucleation of aragonite upon carbonation of calcium oxide and calcium hydroxide at ambient temperatures and pressures: a new indicator of fire-related human activities. *Journal of Archaeological Science* 49:237–248.

Tsartsidou, G., S. Lev-Yadun, R. M. Albert, A. Miller-Rosen, N. Efstratiou, and S. Weiner. 2007. The phytolith archaeological record: strengths and weaknesses evaluated based on a quantitative modern reference collection from Greece. *Journal of Archaeological Science* 34(8):1262–1275.

Twomey, T. 2013. The cognitive implications of controlled fire use by early humans. *Cambridge Archaeological Journal* 23(1):113–128.

Villa, Paola, Francois Bon, and J. C. Castel. 2002. Fuel, fire and fireplaces in the Palaeolithic of western Europe. *Review of Archaeology* 23(1):33–42.

Wadley, L. 2009. Post-depositional heating may cause over-representation of red-coloured ochre in stone age sites. *South African Archaeological Bulletin* 64(190):166–171.

Wattez, J., and M. A. Courty. 1987. Morphology of ash of some plant materials. *Soil Micromorphology.* N. Fedoroff, L. M. Bresson, and M. A. Courty, eds. Pp. 677–683. Plasir: Association française pour l'étude du sol.

Wattez, Julia. 1996. Modes de formation des structures de combustión: approche méthodologique et implications archéologique. In *The Lower and Middle Palaeolithic.* Ofer Bar-Yosef, ed. Forlì: A.B.A.C.O.

Weiner, S. 2010. *Microarchaeology beyond the visible archaeological record.* Cambridge: Cambridge University Press.

Weiner, S., P. Goldberg, and O. Bar-Yosef. 1993. Bone Preservation in Kebara Cave, Israel using on-site Fourier transform infrared spectrometry. *Journal of Archaeological Science* 20(6):613–627.

———. 2002. Three-dimensional distribution of minerals in the sediments of Hayonim Cave, Israel: diagenetic processes and archaeological implications. *Journal of Archaeological Science* 29(11):1289–1308.

Weiner, S., Q. Xu, P. Goldberg, J. Liu, and O. Bar-Yosef. 1998. Evidence for the use of fire at Zhoukoudian, China. *Science* 281(5374):251–253.

Weiner, Steve, Vlad Brumfeld, Ofer Marder, and Omry Barzilai. 2015. Heating of flint debitage from Upper Palaeolithic contexts at Manot Cave, Israel: changes in atomic organization due to heating using infrared spectroscopy. *Journal of Archaeological Science* 54:45–53.

Werts, S. P., and A. H. Jahren. 2007. Estimation of temperatures beneath archaeological campfires using carbon stable isotope composition of soil organic matter. *Journal of Archaeological Science* 34(6):850–857.

Wrangham, Richard W. 2006. The cooking enigma. In *Evolution of the human diet: the known, the unknown, and the unknowable.* Peter S. Ungar, ed. Pp. 308–323. Oxford: Oxford University Press.

———. 2017. Control of fire in the Paleolithic: evaluating the cooking hypothesis. *Current Anthropology* 58(suppl. 16):S303–S313.

Yravedra, J., and P. Uzquiano. 2013. Burnt bone assemblages from El Esquilleu Cave (Cantabria, Northern Spain): deliberate use for fuel or systematic disposal of organic waste? *Quaternary Science Reviews* 68:175–190.