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; Gowlett et al. 1981; Gowlett and Wrangham 2013; James 1989; Pickering et al. 2008; Roe-

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broeks and Villa 2011), but that is not the focus of this paper. However, this continues to be a point of major debate, and the reasons for this underlie, to a large extent, debates about the development of hominin fire use in general (see Sandgathe and Berna 2017 for some discussion of this). What is of concern in this paper is an attempt to achieve some understanding of what researchers interested in the development of fire use really mean when they use specific terms to describe the hominin behavior they see reflected in the archaeological record and how this behavior fits into broader ideas about the nature of the whole process of development of fire use. How are researchers envisioning the long-term process of the development of pyrotechnology, and what terms do they use to describe this? The term most commonly used in the literature in reference to the prehistoric development of fire use is "controlled use." 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; 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" (Shimelmitz 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; Attwell, 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., Shöningen: 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 characteristics, their residues, and 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's [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's [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," "persistent," "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 fire use 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., Aldeias et al. 2012; Dibble et al. 2017; Goldberg et al. 2012; Sandgathe et al. 2011*a*, 2011*b*). 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. 2011*b*) 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 Aldeias 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 lithics.

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 Yaʿakov (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. 2011*a*). 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 Yaʿakov, 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 Vértesszőlős 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

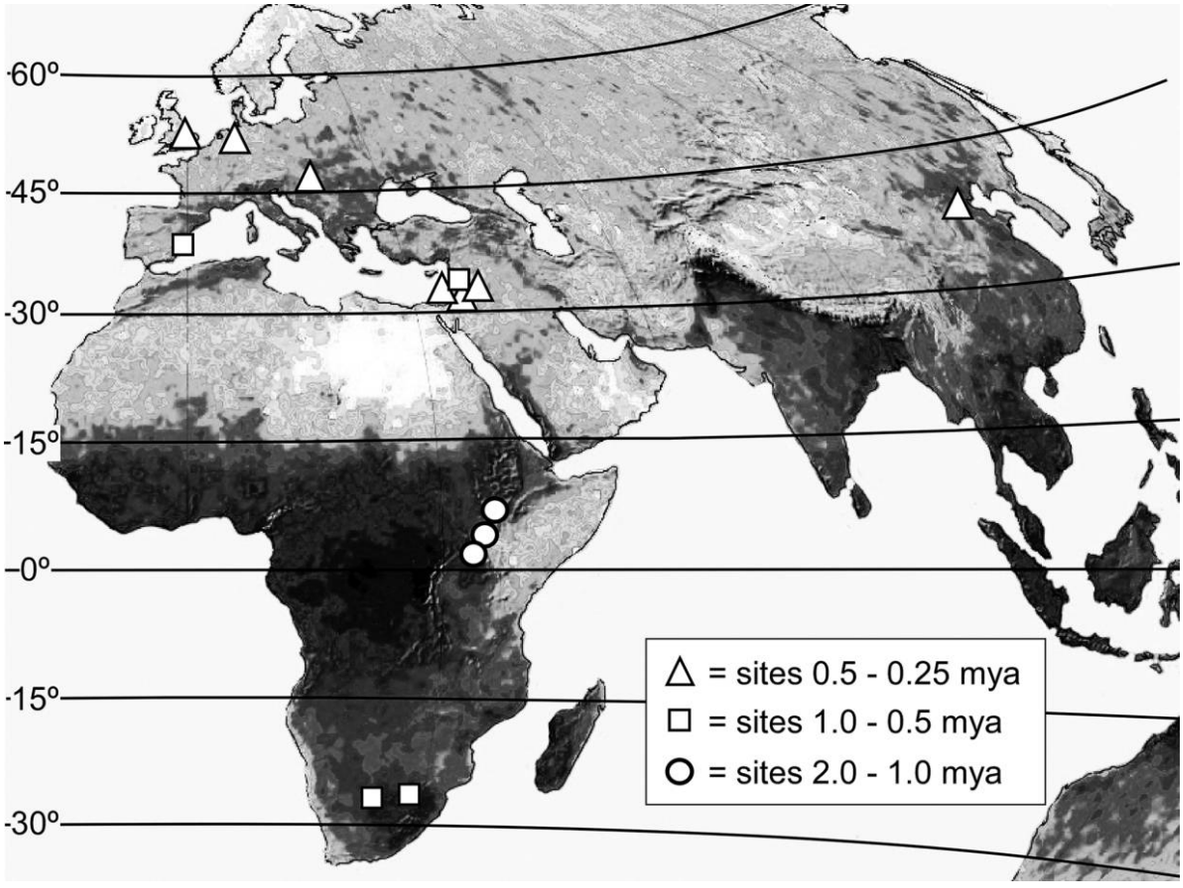

Figure 1. Location of the earliest sites (by region) with potential evidence for hominin fire use mapped onto the frequency distribution of lightning strikes today. In spite of the earliest appearance of hominins in different regions, the earliest evidence for fire use appears to follow a latitudinal 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).

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?

Table 1. Percentage of stratigraphic components per marine isotope stage (MIS)

	MIS										
Evidence for fire	3	4–3	4	5	6	7	8	9	10	11	12–45
0	60.0	25.0	55.0	58.8	81.8	45.0	66.7	100.0	.0	50.0	95.7
1	10.8	.0	25.0	2.1	13.6	20.0	33.3	.0	.0	.0	.0
2	6.9	7.1	12.5	20.6	.0	30.0	.0	.0	.0	8.3	4.3
3	22.3	67.9	7.5	18.6	4.5	5.0	.0	.0	.0	41.7	.0
Total	100	100	100	100	100	100	100	100	0	100	0
Total number of components	130	28	40	97	22	20	3	3	0	12	23

Note. No evidence for fire = 0; possible evidence but insufficiently described or no supporting evidence = 1; good evidence of fire = 2; clear evidence of fire = 3. The total number of components included for each stage is in the bottom row. Some components could only be placed in either MIS 3 or MIS 4 (not one or the other), but the number was significant, and their exclusion from the table would have biased the results. It needs to be stressed that there are a number of potential issues with this type of data:

- The dating of sites and site components and their placement in specific MISs is often difficult, and sometimes there are conflicting data. Because of this, many more sites and site components were reviewed in the literature but were not included here because of issues with their dating.
- Different researchers use different criteria for distinguishing discrete layers, some reporting for lithostratigraphic units and some for archaeological levels.
- For some sites, certain potential evidence for fire might not have been reported, e.g., percent frequencies of burned lithics and burned bone.
- Some researchers might include mention of fire residues for a specific site because they were found in at least one component of the site, but they do not necessarily make it clear whether the residues occur in one, some, or all components.
- For some excavations (especially earlier ones) there might not be confirmation that sediments/residues reported as charcoal or ash were actually such residues.
- We can expect differential preservation patterns at closed versus open sites.

Developing Theoretical Models and Associated Terminology

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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