The Uncertain Origins of Fire-Making by Humans: The State of the Art and Smouldering Questions

Die ungewissen Anfänge der Feuerherstellung durch Menschen: Forschungsstand und schwelende Fragen

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Abstract: *The ability to control fire is a pivotal trait of human culture and likely influenced both the physical and cultural development of our evolutionary lineage. We know fire fundamentally changed our relationship with the world by making previously uninhabitable climates tolerable, inedible foods palatable and more nutritious, and providing a focal point around which complex social relationships could develop. It remains uncertain, however, when and in what manner fire became an integral part of the technological repertoire of our early ancestors. This gap in our knowledge prevents a full understanding of how fire affected our physical form and cultural lifeways. The long and drawn out process by which fire progressed from simply being a close companion in the natural environment to becoming a resource exploited opportunistically by hominins eventually led to greater control of fire. At this point, fire was largely 'tamed' through careful maintenance and transported from place to place. Ultimately, likely through a combination of serendipity and experimentation, humans discovered that they could make fire for themselves whenever and wherever they liked, providing a profound new freedom to control their environment, cook their food and produce new materials at will.*

This article provides an overview of the current state of our understanding of fire use, and more specifically, fire-making in the Paleolithic. There is currently much debate in the field surrounding this issue, and it is stressed herein that the only way to definitively infer any one hominin group could make fire is to identify the tools they used to do so. Therefore, much attention is paid to how archaeologists have attempted to identify fire-making tools in the archaeological record, primarily using experimental archaeology coupled with microwear analysis. Through these efforts, it appears stone-on-stone percussive fire-making using flint and pyrite was a skill first practiced by at least some groups of late Neanderthals, though its origins could be much older. Conversely, preservational problems associated with the wood-on-wood friction fire-making make it extremely difficult to assess the antiquity of this method. Lingering questions regarding early fire-making innovations and possible avenues for future research are discussed.

Keywords: *Paleolithic, fire-making, experimental archaeology, microwear analysis, Neanderthals, human evolution*

Zusammenfassung: Die Fähigkeit, Feuer zu kontrollieren ist ein entscheidender Charakterzug menschlicher Kultur und hat wahrscheinlich sowohl die physische als auch die kulturelle Entwicklung unserer Abstammungslinie beeinflusst. Wir wissen, dass das Feuer unsere Beziehung zur Welt grundlegend geändert hat, indem es vorher unbewohnbare Klimazonen erträglich gemacht, ungenießbare Nahrung genießbar und nahrhafter gemacht, und indem es einen Mittelpunkt geboten hat, um den herum sich komplexe Sozialbeziehungen entwickeln konnten. Es bleibt jedoch ungewiss, wann und in welcher Weise Feuer ein integraler Bestandteil des technologischen Repertoires unserer frühen Vorfahren wurde. Diese Wissenslücke verhindert ein völliges Verständnis davon, wie Feuer unsere Körperform und unsere kulturellen Verhaltensweisen beeinflusste. Der lange und langwierige Prozess, in dessen Verlauf Feuer von einem engen Gefährten innerhalb der natürlichen Umwelt zu einer Ressource wurde, die opportunistisch von Menschen ausgebeutet wurde, führte im Folgenden zu einer umfangreicheren Kontrolle des Feuers. An diesem Punkt war das Feuer durch sorgfältige Inganghaltung weitgehend ‚gezähmt' und wurde von einem Platz zum anderen transportiert. Schließlich entdeckten Menschen, wahrscheinlich durch eine Kombination aus glücklichem Zufall und Experimentieren, dass sie selbst Feuer herstellen konnten wann und wo immer sie wollten. Auf diese Weise schufen sie sich eine tiefreichende Freiheit, ihre Umwelt zu kontrollieren, ihre Nahrung zu kochen und willentlich neue Materialien herzustellen.

Der vorliegende Beitrag bietet einen Überblick über den gegenwärtigen Kenntnisstand zur Feuernutzung und, genauer, zur Feuerherstellung im Paläolithikum. Gegenwärtig gibt es lebhafte Diskussionen im Umfeld dieses Themas, und es wird hier betont, dass der einzige Weg, um definitiv erschließen zu können, dass irgendeine Menschengruppe Feuer herstellen konnte, in der Identifikation von Werkzeugen besteht, mit denen sie dies tun konnten. Aus diesem Grunde liegt das Augenmerk vor allem darauf, wie Archäologen versucht haben, Werkzeuge zur Feuerherstellung im archäologischen Befund zu identifizieren, indem sie in erster Linie Erkenntnisse der experimentellen Archäologie in Verbindung mit Ergebnissen der Mikrogebrauchsspurenanalysen betrachteten. Als aussichtsreiche Kandidaten erwiesen sich bifazielle Werkzeuge aus dem Kontext des Moustérien mit Acheuléen-Tradition (MTA), die unbestimmte mineralische Mikrogebrauchsspuren trugen. Es wurde beobachtet, dass diese Spuren stets auf den Flächen dieser Faustkeile in Verbindung mit Schrammen – und in manchen Fällen C-förmigen Schlagmarken – auftraten, die nahezu immer parallel zur Längsachse des Werkzeuges ausgerichtet waren; zusammengenommen deutete dies auf eine einheitliche Einwirkung schräg gerichteter Schlagenergie hin. Sehr ähnliche Spuren wurden in Experimenten zur Feuerherstellung erzeugt, bei denen die Fläche eines Faustkeils als Schlagfläche verwendet wurde, gegen die man mit einem Stück Pyrit schlug. Auf diese Weise ließ sich ohne Probleme ein Funkenhagel erzeugen, der leicht in Zundermaterial aufgefangen werden konnte, um dieses zum Glühen zu bringen. Solche mutmaßlichen Spuren der Feuerherstellung wurden bisher auf Dutzenden französischer MTA-Faustkeile festgestellt, so dass es nach diesen Analysen den Anschein hat, dass die Feuerherstellung durch das Schlagen von Pyrit auf Feuerstein eine Fähigkeit war, die erstmals – zumindest regional – durch einige Gruppen später Neandertaler praktiziert wurde, wobei ihre Ursprünge viel älter sein könnten. Auf der anderen Seite ist es aufgrund erhaltungsbedingter Probleme extrem schwer, für eine ebenfalls vorstellbare Feuererzeugung mittels Reibung von Holz auf Holz die zeitliche Tiefe dieser Methode abzuschätzen. Offene Fragen in Bezug auf frühe Innovationen bei der Feuerherstellung und mögliche Ansätze für zukünftige Forschungen werden diskutiert.

Schlagwörter: Paläolithikum, Feuerherstellung, experimentelle Archäologie, Mikrogebrauchsspuren-Analyse, Neandertaler, menschliche Evolution

[I am] inclined to think that not far from the invention of fire must rank the invention of doubt.

Thomas Henry Huxley, biologist (1825–1895)

Introduction

The human acquisition of fire set our hominin ancestors on a trajectory that would, in the end, culminate in a society utterly dependent on this natural resource for its survival. Yet, our personal relationship with fire has become greatly diminished in the modern era compared to our prehistoric ancestors. Save for gas stoves, candles and the occasional barbeque, fire is not often something we experience day-to-day as it would have been in the past. Nevertheless, fire remains the basis for the vast majority of our technology and comforts, despite being largely hidden away. Without distant coal-fired power plants, internal combustion engines, furnaces and the like, life as we know it today could not exist. It is perhaps for this reason that exploring the beginnings and development of fire as an adaptive tool by humans retains the interest of the public at large and scientific researchers alike: it is key to understanding who we are as a species, and as a society.

The manipulation and production of fire is an exclusively human trait, arguably to a greater extent than both tool use and language, and one that eventually became universal within the *Homo* lineage (Goudsblom 1986). However, as will become readily apparent below, the role that fire has played in human evolution remains highly contentious and provides a perpetual source of inspiration and healthy scepticism among researchers interested in this fascinating topic. The purpose of this paper is to provide a broad overview of the history of early fire research and to present more recent findings in the field, especially with regards to discerning the origins of artificial fire production among Paleolithic peoples.

The benefits conferred by fire unto those brave enough to wield it are manifold (for an overview, see Clark and Harris 1985). It is often said that range expansion into naturally uninhabitable parts of the world is one of the hallmarks of modern behavior in humans (McBrearty and Brooks 2000). One could, in many regards, consider fire the ultimate 'range expander'. Fire buffered humans from the cooler conditions associated with a spatial expansion outward to more northerly latitudes and upward into higher altitudes (Oakley 1956; Weiner et al. 1998; Rolland 2004; Gowlett 2006; but see Perlès 1977; Roebroeks and Villa 2011a). Since fire can act as a deterrent of dangerous predators (Goudsblom 1986; Brain and Sillen 1988), it has been postulated that hominins were unable to securely occupy cave sites until regular use of fire provided a means to drive out cave-dwelling competitor species like hyenas or bears (Oakley 1956). The added security also translated to added comfort, since fire is an effective means of cleansing sleeping areas of old grass bedding and parasites living therein (Goldberg et al. 2009; Wadley et al. 2011), and the smoke from fires helps to keep pesky biting flies and swarming mosquitoes at bay (Binford 1978; Sharp and Sharp 2015). Temporally, fire extended the day by providing light to work by and cutting the night chill. The social nature of eating and working around a fire led to an expansion of communication and solidarity within groups (Dunbar 1998; Dunbar and Shultz 2007; Dunbar and Gowlett 2014; Wiessner 2014) that fostered an environment ripe for cultural and technological advances. Regarding the latter, fire improved the workability of wooden (Ennos and Chan 2016; Aranguren et al. 2018; Rios-Garaizar et al. 2018) and stone tools (Brown et al. 2009; Schmidt et al. 2013), as well allowed for the synthesis of entirely new materials like birch bark pitch (Kozowyk et al. 2017), which was used as a hafting material (Koller et al. 2001; Mazza et al. 2006). Fire was also widely used 'off-site' as a tool to aid in hunting or to encourage the growth of edible plants preferred by prey species or by the hominins themselves, in some instances ultimately – by chance or by design – reconfiguring entire landscapes (for an extensive ethnographic and archaeological overview of these phenomena, see Scherjon et al. 2015 and the sources therein). Finally, of the advantages offered by fire use, the ability to cook food is often the most discussed. Cooking with fire expanded the range of foods consumed by hominins, both in variety and quality (Goudsblom 1992), including eliminating toxins (Stahl 1984) or making it easier to access foods with tough skins like tubers (Schnorr et al. 2015), as well as conferring a number of energetic and health benefits: increased caloric savings (Boback et al. 2007; Carmody and Wrangham 2009; Groopman et al. 2015), reduced cost of digestion (Boback et al. 2007; Carmody et al. 2011), decreased time and effort spent chewing (Dominy et al. 2008; Organ et al. 2011; Fonseca-Azevedo and Herculano-Houzel 2012; Zink et al. 2014), and decreased risk of food-borne illness (Smith et al. 2015; but see Speth 2017).

Humans did not invent fire, but instead harnessed it, giving purpose to an otherwise mostly unwieldy and destructive force. In line with fire myths that claim fire to be a gift instead of a learned skill (see Frazer 1930), it is inferred that hominins initially collected fire from natural conflagrations caused by lightning, volcanism or, more infrequently, the spontaneous combustion of coal, oil-shale or other concentrations of organic plant matter (Oakley 1956). However, using fire does not necessarily equate to being able to produce it. The purpose of my recently defended doctoral research project (Sorensen 2018) was to move ‘beyond Prometheus’ and discern when humans no longer needed to rely on higher (natural) forces to provide them with fire, but instead could regularly make it for themselves. The incorporation of fire into the human toolkit was very probably not a singular event, as most fire myths would lead one to believe. Instead, it was an extended and likely punctuated process where hominins first became comfortable around fire, which, through trial and error, eventually led to its acquisition and use and, ultimately, to the ability to produce it at will. When exactly humans (or their ancestors) first developed these abilities is still a source of considerable debate (Wrangham 2009; Roebroeks and Villa 2011a; Berna et al. 2012), as unfortunately for archaeologists, evidence for fire production prior to the Holocene has been notoriously difficult to identify in the archaeological record (see below).

As pointed out in a recent publication by Sandgathe and Berna (2017), the subject of Paleolithic fire use has become a hot-button issue in the field of archaeology in recent decades. The primary overarching questions being pursued include: When did hominins begin using fire? What were the behavioral and physiological consequences of infrequent or regular fire use by humans and how do these manifest? When (and where) did fire use become a ‘fixed’ or ‘habitual’ element within the human technological repertoire? And when did hominins begin to make fire for themselves? This paper concerns itself principally with the final two questions, these focusing more on the latter stages of humankind’s love affair with fire.

The prehistory of fire and hominin fire use

Fire has been a global phenomenon since at least the Devonian period, when the first evidence of fire in the form of fusain or fusinite (fossil charcoal) is observed in the geological record (Scott 2000). Fusain layers, presumably products of ancient fires ignited by lighting or spontaneous combustion of decaying organic matter, are also a common occurrence within Carboniferous coal beds (see Komarek 1972). Other notable examples of ancient fire include fire scars on Triassic trees (Byers et al. 2014), charcoals associated with dinosaur bones dating to the Cretaceous (Brown et al. 2013), and heated fragments of chert (Bordes 1957) and bone (Hendey 1976) from Miocene deposits. Thus, by the time our human ancestors arrived on the scene, fire was already a common occurrence in many environments, and many plants and animals had become at least accustomed to coping with wildfires, while other more pyrophilic species had developed adaptions that made them to varying degrees reliant on the actions of fire for their survival. Among animals, this is reflected in many modern species that show little to no flight response to wildfires, some are attracted to smoke, take advantage of recently burned tracts of land for grazing or foraging, or actively interact with burning fires (Komarek 1969), including some primates (Pruetz and LaDuke 2010; Parker et al. 2016; Pruetz and Herzog 2017). Even some birds of prey in Australia often congregate near the edges of bushfires to take advantage of fleeing animals and insects and have been observed actively lighting grass fires by picking up smouldering twigs from one fire and dropping them in unburned areas to ignite another (Bonta et al. 2017).

This familiarisation with natural fire encompasses the hypothesized first stage of hominin interaction with fire (Parker et al. 2016), of which there are generally considered three or four, depending on which source one consults. Sandgathe (2017) provides a good overview of the slightly different configurations of these progressive steps towards greater complexity of fire use that have been proffered in the past (see Frazer 1930; Goudsblom 1986; Burton 2009; Pruetz and LaDuke 2010; Parker et al. 2016; Chazan 2017), ultimately combining and distilling them down to four major stages: 1) habituation to natural fire, 2) use of fire, 3) maintenance of fire, and 4) manufacture of fire.

As already alluded to above, the hominin fire habituation phase itself could be subdivided into increasingly more intimate interactions with fire, beginning with the basic suppression of the flight response when encountering a natural fire (Clark and Harris 1985) and being able to negotiate a burning landscape calmly without panicking (Pruetz and LaDuke 2010), and then progressing to identifying and exploiting the beneficial consequences of fire for personal gain. Pruetz and Herzog (2017) outline a few possible reasons for why hominins might have been drawn to fire-modified landscapes: 1) changes in the distribution of and access to food, 2) improvements in overland travel, and 3) decreased threat of predation. The burning away of grassy vegetation allows for easier acquisition of hidden fruits, seeds or tubers, while also leaving behind lightly cooked small vertebrate and invertebrate species (Sponheimer et al. 2005a, b), the latter potentially leading to increased insectivory among some groups (Burton 2009; Bogart and Pruetz 2011; Herzog et al. 2016). Moreover, the reduction of dense vegetation in burned swaths not only reduces the energy required for locomotion, but may also be attractive because of enhanced predator detection (Herzog 2015).

This passive use of fire would eventually lead to an active use of fire (Stage 2). This purposeful interaction with fire may have been limited at first, with hominins perhaps feeding a naturally burning fire in place to artificially prolong its presence, presumably to be used for warmth or for cooking. This would likely have evolved into the ability to transport fire away from where it was initially collected to be built anew and maintained in another location. We generally assume these transitions would have occurred in landscapes where lightning-caused fires predominate. However, as hypothesized by Medler (2011) and Bailey and colleagues (2000), zones of long-term active volcanism (i.e., the African Rift Valley) may have also provided some hominins with extended periods of acclimatisation to a fire-prone environment that they would have eventually learned to use to their advantage. These authors suggest that, perhaps initially, near-surface magma chambers could have been exploited by hominins as warm sleeping locations, while active lava seeps would have provided hominins with regular, predictable sources where fire could be obtained.

Determining when and where these major transitions took place is at the forefront of early fire research, primarily in that these moments in prehistory are very challenging to pin down. This is partially due to these being gradual processes – much like evolution itself – that do not possess a definitive moment of discovery followed by ubiquitous use of fire technologies. Or, if there were innovative moments where the utility of fire was realized or when techniques for producing fire were learned, these would not have been one-off events, but were instead likely discovered, lost and rediscovered numerous times and in numerous places by different peoples (Oakley 1961). Moreover, incorporation of fire into the human tool kit would have manifested differently under different environmental situations, further muddying the waters. Here, I will outline some of the ways in which researchers have attempted to infer the hominin progression through the various stages of anthropogenic fire use.

Transition I: Habituation to natural fire (Stage 1) to anthropogenic fire use (Stage 2)

Interestingly, the oldest proposed evidence for hominin fire use is not archaeological, but physiological, and stems from the possible consequences of an inferred introduction of cooked foods into the diet of early *Homo*. The incorporation of more easily digested cooked foods may have been responsible for shortening the human gut and redirecting calories to the brain that would normally go towards digestion (Aiello and Wheeler 1995), ultimately contributing to an increase in brain size in hominins beginning around 1.9 Ma with the appearance of *Homo erectus* (Wrangham 2009). This model has been challenged by Cornélio and colleagues (2016), who argue that the use of stone tools by pre-erectine hominins allowed for more efficient processing of food, thereby introducing a greater proportion of meat into their diets. This increase in foraging efficiency, they suggest, better explains this relative increase in brain size given the lack of associated archaeological evidence for fire use during this period. In a similar vein, an earlier introduction of difficult to access brains and marrow into pre-hominin diets through swift secondary exploitation of carcasses using large stones to break open skulls and long bones may have also provided a fire-free means to obtain extra calories that were redirected towards building larger brains (Thompson et al. 2019).

Other physiological changes have been purported to reflect fire use by early hominins. It has been postulated that the onset of human hairlessness may have stemmed from semi-regular use of fire, either due to the thermoregulatory benefits conferred by fire (Russell 1978), or perhaps from the need to reduce the risk of one's fur accidentally being set alight by errant sparks while sitting around the hearth (Medler 2011). While bipedality would not have been a consequence of fire use, it may well have facilitated the early active use of fire, both for the collection of firewood and for carrying fire from one place to another (Medler 2011).

Despite these possible fire-forged shifts in early hominin physiology, there is effectively no archaeological evidence to date of fire having been used by hominins in Africa (or anywhere else) until around 1.5 Ma, roughly 400,000 years after the appearance of *Homo erectus*. The earliest Lower Paleolithic sites containing evidence for fire use, usually in the form of localized patches of thermally altered sediments, lithic artifacts or bones, are found in Africa and include the Kenyan sites Koobi Fora (Bellomo 1993, 1994; Bellomo and Kean 1997; Harris et al. 1997; Hlubik et al. 2017, 2019) and Chesowanja (Isaac 1982; Gowlett et al. 1981, 1982), and Gadeb in Ethiopia (Clark and Kurashina 1979; Barbetti et al. 1980; Barbetti 1986), with later occurrences in South Africa around 1.0 Ma at Swartkrans (Brain and Sillen 1988; Brain 1993; Pickering et al. 2005) and Wonderwerk Cave (Beaumont 2011; Berna et al. 2012), and at Olorgesailie in Kenya (Isaac 1977).

After 1.0 Ma, anthropogenic fire use begins to appear outside of Africa. Just outside of Africa in the Levant, Gesher Benot Ya'akov (Israel), which dates to ca. 790 ka, provides the earliest and best evidence for recurrent fire use at an early hominin site as evinced by 'phantom hearths' comprised of clusters of heated lithic artifacts and small carbonized plant remains (Alperson-Afil and Goren-Inbar 2006; Alperson-Afil et al. 2007; Alperson-Afil 2008), though the extent of fire use at this site makes it, for the moment, an outlier among the handful of other fire-bearing sites from this period. In Asia, the Chinese sites Xihoudu and Yuanmou contain charcoal and heated bone that could be representative of anthropogenic burning as early as >1.5 Ma (Jia 1985), though these early dates have been contested (see James 1989). Perhaps the most well-known of the Chinese early fire sites – if only for the decades of debate surrounding the site – is Zhoukoudian (formerly Choukoutien or Chou-kou-tien in early literature), which possesses multiple lines of evidence for anthropogenic fire use spanning upwards of half-a-million years, beginning around 800 ka (Black 1932; Wu 1999; Gao et al. 2017; for claims disputing these interpretations, see Binford and Ho 1985; Weiner et al. 1998; Goldberg et al. 2001).

In Europe, perhaps the earliest reported evidence for anthropogenic fire use appears north of the Black Sea on the Taman peninsula at the site of Bogatyri in Russia, at around roughly 900 ka (Bosinski 2006). Other early European sites exhibiting strong evidence for fire use include the Spanish sites of Cueva Negra del Estrecho del Río Quípar (ca. 800 ka) (Rhodes et al. 2016; Walker et al. 2016) and La Solana del Zamborino (ca. 750 ka) (Botella López et al. 1976; Scott and Gibert 2009; though recent redating of this site suggests it is much younger, around 408-300 ka, see Álvarez-Posada et al. 2017). Both sites possess purported combustion features containing large amounts of charcoal, charred/combusted bone and heated lithic remains, with the Zamborino feature apparently encircled by quartzite cobbles exhibiting thermal alteration of the surfaces facing the interior of the hearth. Fire evidence is comparatively weak at other roughly contemporaneous European sites like the Atapuerca complex in Spain (Expósito et al. 2017), or the somewhat younger Boxgrove site in England (Roberts and Parfitt 1999), which only possess occasional dispersed charcoal fragments that could be attributed either to anthropogenic or natural burning. For a more detailed discussion of these early fire sites, see Gowlett and Wrangham (2013). And for a more critical take on a number of these same sites, see James (1989).

Transition II: Fire use (Stage 2) to fire maintenance (Stage 3)

As hominins became more accustomed to using fire, they would have become increasingly reliant on the various advantages it affords, likely increasing the regularity with which they would have used it. This regularity perhaps went beyond the frequency with which these groups would have encountered fire naturally, thus reflecting more frequent transportation and maintenance of fires once collected, which, in turn, facilitated the appearance of hearths and combustion features in less fire-prone locations like the interiors of caves. This more frequent use of fire, coupled with the greater protection from erosion afforded by placing hearths inside caves, likely increased the visibility of fire in the archaeological record after this point.

Convincing evidence for anthropogenic fire use in Europe does not begin to appear with any regularity until around 400-300 ka, so from around Marine Isotope Stages (MIS) 11-9 onward (Roebroeks and Villa 2011a). Whether or not this increase in fire sites coincides with the advent of fire production technology or just more concerted efforts by early Neanderthals to conserve and transport their fire is difficult to say at the moment. Among the earliest sites from this transitional period exhibiting single or multiple combustion zones or hearths are Vértesszőllős in Hungary (Vértes and Dobosi 1990), Terra Amata in southern France (de Lumley 1966, 2006; Villa, 1982, 1983), Menez-Dregan in northwest France (Monnier et al. 2016; Ravon 2017) and Beeches Pit in the United Kingdom (Gowlett et al. 2005; Preece et al. 2006). While Schöningen in Germany had the potential to be counted among these early European sites with strong evidence of fire use, a more recent study has shown the purported combustion structures at this site to be natural geologic features (Stahlschmidt et al. 2015); though, a handful of heated natural flint fragments do indicate fire (natural or anthropogenic) made an appearance at the site during this period (Richter and Krbetschek 2015). This trend of increasing fire use continues through MIS 6 (ca. 191-130 ka; Lisiecki and Raymo 2005), with stratified deposits exhibiting recurrent, strong signals for anthropogenic burning occurring at, for example, Bolomor Cave in Spain (Fernández Peris 2007; Sañudo et al. 2016), Payre in southern France (Moncel 2008; Daujeard and Moncel 2010), La Cotte de St. Brelade on the island of Jersey (Callow et al. 1986), as well as extensive evidence for fire at open air sites like Biache-Saint-Vaast and Therdonne in northern France (Hérisson et al. 2013). This pattern of recurrent fire use is perhaps best expressed in a number of late Lower and early Middle Paleolithic Israeli sites exhibiting stacked central hearth features/combustion areas, the earliest example appearing at Qesem Cave 400-300 ka (Karkanas et al. 2007; Shahack-Gross et al. 2014; Blasco et al. 2016), and a bit later at Tabun (Jelinek et al. 1973; Shimelmitz et al. 2014), Kebara (Schiegl et al. 1996; Speth 2006; Meignen et al. 2009; Albert et al. 2012) and Hayonim caves (Goldberg 1979; Schiegl et al. 1996; Meignen et al. 2009), as well as at the open air site of Nesher Ramla (Friesem et al. 2014; Zaidner et al. 2014, 2016).

Fire evidence appears in the archaeological record with even greater regularity in Europe during the latter period of Neanderthal existence, from the Last Interglacial through the late Last Glacial periods (MIS 5e-3, ca. 130-35 ka). Here, one sees a marked increase in the number of archaeological sites exhibiting overt combustion features and hearths (sometimes occurring as stacked features suggesting repeated relighting of fires in the same location), and, in many cases, greater proportions of fire proxies like heated lithics or bone (for a comprehensive list of Lower and Middle Paleolithic sites with fire evidence, see Dataset S1 in Roebroeks and Villa, 2011a; Rosell and Blasco 2019). Included among the sites with well-preserved evidence for recurrent fire use by Neanderthals are, for example, Abric Romaní (Vaquero et al. 2001; Carbonell 2012, and papers therein; Courty et al. 2012; Vallverdú et al. 2012) and El Salt (Dorta Pérez et al. 2010; Mallol et al. 2013; Rodríguez-Cintas and Cabanes, 2017; Vidal-Matutano, 2017) in Spain, Pech de l'Azé IV (Dibble et al. 2009, 2018a [and papers contained therein]; Sandgathe et al. 2011a; Turq et al. 2011), Roc de Marsal (Sandgathe et al. 2011a; Aldeias et al. 2012; Goldberg et al. 2012), Combe Grenal (Bordes, 1955, 1972; Binford 2007) and Grotte Mandrin (Giraud et al. 1998; Vandevelde et al. 2017, 2018) in France, Gruta da Oliveira in Portugal (Angelucci and Zilhão 2009; Richter et al. 2014; Zilhão et al. 2016), Sesselfelsgrotte in Germany

(Richter 1997, 2006; Richter et al. 2000), Fumane Cave in Italy (Peresani et al. 2011), and Biśnik Cave in Poland (Cyrek et al. 2014, 2016). As the list above demonstrates, well-stratified sites with fire evidences are primarily found in cave deposits, due in large part to the fact that karstic systems act as sediment traps. There are, however, a number of open air sites also exhibiting strong, and in some cases, recurrent signals of fire use, including Neumark Nord 2 in Germany (Pop et al. 2016), Port Racine in France (Cliquet 1992), Ripiceni Izvor in Romania (Păunescu 1993; Mertens 1996; Cârciumaru 1999), Księcia Józefa in Poland (Zieba et al. 2008, 2010), and Starosele in Crimea (Formozov 1958; Demidenko 1998; Marks et al. 1998).

In parallel to the European fire record, there appears to be a more or less coeval increase in evidence for anthropogenic fire use in the African Middle Stone Age (MSA) archaeological record. The majority of these sites with strong anthropogenic fire signals are located in southern Africa (see Bentsen 2014 for an extensive overview). Notable examples include the open-air site of Kalambo Falls in Zambia, which exhibits a large patch of baked earth around 1 m in diameter associated with numerous charred wooden artifacts (Clark 1969, 2001), and the South African cave and rockshelter sites of Pinnacle Point (Marean et al. 2004, 2010; Karkanas and Goldberg 2010), Klasies River (Butzer 1978; Singer and Wymer 1982; Deacon and Geleijnse 1988; Deacon 1989; Henderson 1992; Jacobs et al. 2008; Wurz et al. 2018), Diepkloof (Parkington and Poggenpoel 1987; Rigaud et al. 2006; Jacobs et al. 2008; Tribolo et al. 2009; Texier et al. 2010; Miller et al. 2013), Blombos (Henshilwood et al. 2001a, b, 2002; Jacobs et al. 2006; Tribolo et al. 2006; Mourre et al. 2010; Discamps and Henshilwood 2015), and Sibudu (Wadley 2001, 2006, 2012; Schiegl et al. 2004; Cain 2005; Sievers 2006; Wadley and Jacobs 2006; d'Errico et al. 2008; Goldberg et al. 2009), all of which possess superimposed hearth structures. Sibudu and Diepkloof rock shelters also exhibit recurrent layers of carbonized plant remains and ash interpreted as evidence for systematic burning of old bedding (Goldberg et al. 2009; Wadley et al. 2011; Wadley 2012; Miller et al. 2013), while Klasies River Cave presents early evidence for the cooking of starchy food (Larbey et al. 2019). At Jebel Irhoud in Morocco, which has produced what are interpreted as the earliest *Homo sapiens* fossils yet known (Hublin et al. 2017), significant evidence for fire use is evinced by probable combustion features containing charcoal and high percentages of fire-affected lithic artifacts (37% of the assemblage) and faunal remains (5-25%, depending on the layer) (Richter et al. 2017). For a list of other North African sites with combustion features, please refer to Supplementary File 1 in Will et al. (2019), and the references listed therein.

It is entirely possible that the diachronic trend of increasing fire evidence in both Europe and Africa has little to do with greater regularity of hominin fire use through time, but instead may be related to taphonomic bias; that is, the older the deposit, the less likely fire remains (or any archaeological material, for that matter) will preserve (Surovell and Brantingham 2007; Sandgathe et al. 2011b). However, this idea is somewhat contradicted in a later paper by Surovell and colleagues (2009). Here they demonstrate through an updated taphonomic bias model that the rate at which archaeological materials are destroyed is not constant through time, but instead declines with the age of a site. In other words, "If a site can survive its first 10,000 years of existence, its annual probability of destruction is reduced to approximately 0.01%, or a 1 in 10,000 chance" (Surovell et al. 2009, 1718). If this is true, then one could expect differences in the preservation of fire remains between archaeological deposits laid down under different depositional conditions and subjected to variable intensities of post-depositional processes, these likely being mediated by prevailing climatic conditions.

Turning back again to the European Middle Paleolithic, other researchers have pointed to various cultural responses to changes in climate as the driving force behind variability in Neanderthal fire use. In their original 2011 article, and reinforced in later papers (Sandgathe et al. 2011b; Dibble et al. 2017, 2018b; Sandgathe 2017), Sandgathe et al. offer a unique new take on the relationship between Neanderthals and fire. These authors propose that reduced fire evidence in archaeological layers attributed to cold weather periods at Pech de l'Azé IV and Roc de Marsal in the Dordogne (France) indicates Neanderthals, lacking the ability to make fire, were reliant on harvesting flames for their hearths from natural fires ignited by lightning strikes, these being less prevalent during colder climatic conditions (Sandgathe et al. 2011a, b; Dibble et al. 2017, 2018b). However, more recent studies by the author (Sorensen 2017; Sorensen and Scherjon 2018) have challenged this hypothesis from a number of angles and found it to be lacking. Sorensen (2017) demonstrates that lightning and fire regimes would not have been reduced to the point to preclude regular access to natural fires in the region by Neanderthals, had they indeed been reliant on such sources. The paper also points to other contemporaneous sites in the region, primarily Combe Grenal, which presents evidence of fire use throughout its sequence, including during cold weather periods. This is further supported by the more recent findings of Vandevelde and colleagues (2017, 2018) at Grotte Mandrin in south-eastern France, where repeated deposition of soot films in carbonate deposits within the cave makes a strong case for regular fire use at the site, even during cold periods, lending credence to the idea that these Neanderthals were certainly proficient at controlling fire, and possibly even making fire.

Sorensen (2017) goes on to highlight a variety of conditions experienced during cold climatic episodes that could have negatively impacted the production and preservation of fire traces in the archaeological record, even had fire use remained a regular component of the Neanderthal toolkit. The recurrent use of a camp or habitation site is often linked to subsistence strategies, these being related to the seasonal presence of animal or plant resources (Delagnes and Rendu 2011; Rendu et al. 2011). Relative proximity to wood fuel sources would also likely have been a factor in site selection, as it is among modern Arctic-dwelling hunter-gatherers (Binford 1978, 1980). During colder glacial periods, reduced fuelwood availability would have led to increased fuel economisation – especially within the immediate vicinity of upland sites like Roc de Marsal and Pech de l'Azé IV, since trees would have been largely restricted to river/stream valleys. Under such conditions, fire use may have been a matter of choice, where Neanderthals chose to use or not use fire based on the costs and benefits using fire would entail (Henry 2017; Henry et al. 2018). Moreover, increased mobility brought on by a reliance on highly mobile reindeer, which comprise the majority of the prey species observed at these sites during cold climatic intervals (presumably MIS 4 and early MIS 3), would have changed how and when Neanderthals used these sites. Reindeer tend to follow an annual migration route characterized by aggregation periods during the spring and especially in the fall (cf. Burch 1972). This means the occupation of certain sites would likely have been more seasonal and largely dependent on where the site was located along the reindeer migration route. However, which route reindeer follow during the spring or fall migration is variable and often unpredictable (Burch 1972; Binford 1978), meaning that a site may not have been occupied at all some years if alternative routes were taken. Moreover, given the speed with which reindeer herds can travel (up to 65 km a day, averaging 25-30 km; Burch 1972), the time spent at some sites may have been very limited, suggesting a potential reduction in the intensity and frequency with which some sites along this route are occupied, thereby also affecting the frequency and intensity of fire use.

We attempted to test how the abovementioned conditions might influence fire signals (specifically, heated lithic artifact concentrations) at archaeological sites through computer-based simulations using a custom-built model called 'fiReproxies' (Sorensen and Scherjon 2018). We found that under certain conditions – namely those that could be expected during colder climatic periods – estimated heated lithic percentages can be expected to be very low, even if fire is used during every occupation of a site within an archaeological layer. Under such conditions, the low percentages of heated lithics relate primarily to the interplay between fuel economisation (i.e., fewer, smaller, short-term fires), reduced site use frequency and higher sedimentation rates, though other variables like increased surface area available for occupation also factor into producing weaker archaeological fire signatures, thus lending credence to the assertions made by Sorensen (2017). Ultimately, it is suggested that having the ability to make fire at will would have facilitated this use of short-lived, more task-specific fires since this practice would largely negate the need to constantly fuel their fires as a means of preserving this precious resource. These results have major implications for how archaeologists should interpret fire use signals in layers where small amounts of heated lithics are present, but where primary evidence for fire use (i.e., intact combustion features) are not preserved.

Other factors to consider regarding reduced use of fire unrelated to the ability to produce it includes boiling food in perishable containers (e.g., animal paunches, bladders or hides, or possibly birch bark containers), which would have required less fuel and smaller fires than stone-boiling or roasting (Speth 2012, 2015), thereby reducing the intensity of fire use (and the resultant archaeological fire signals). Other fire-free methods for preparing food (e.g., pounding, slicing or fermentation) could have further reduced the need to use fire on a day-to-day basis under conditions where fuel is scarce (Glover et al. 1977; Heaton et al. 1988; Carmody and Wrangham 2009; Carmody et al. 2011; Zink et al. 2014; Zink and Lieberman 2016; Castel et al. 2017; Speth 2017). Moreover, other cultural adaptions, such as the use of clothing and/or shelter (Chu 2009; Gilligan 2017), or physiological adaptions, such as increased muscle mass or brown adipose tissue (BAT), metabolic acclimation and/or perhaps even microbiotic responses (Scholander et al. 1958a, b; Hammel et al. 1959; Steegmann et al. 2002; Aiello and Wheeler 2003; Chevalier et al. 2015), could have provided enough protection from the elements to negate the absolute need for fire for thermoregulation in instances where making a fire was not possible or the procurement of fuel was prohibitively costly (for overviews, see White 2006; Churchill 2014; Hosfield 2016; MacDonald 2018). Indeed, the overall effectiveness of fire for thermoregulation, especially while sleeping, has been questioned (Sørensen 2009). In these instances, however, a reduction in the frequency of fire use is not the same as a reduction in regularity of use, nor is it necessarily related to a reduced reliance on fire (Sorensen 2017; Sorensen and Scherjon 2018). It has also been suggested that Neanderthals had at some points acquired the ability to make fire but then lost it (Sandgathe 2017), as has been demonstrated ethnographically among the Northern Ache of Paraguay (e.g., Hill et al. 2011). This example is a particularly exceptional case, however, and largely does not apply to Pleistocene hunter-gatherers, in that the prevalence of fire at the edges of the Ache territory caused by adjacent slash-and-burn agriculturalists made for a readily exploitable resource that allowed the Ache to safely forget the methods for making fire they possessed prior to contact with these outside groups. Therefore, once having acquired the ability to make fire, it is unlikely that this exceptionally useful tool would simply have been forgotten by Neanderthal or other hominin groups, barring very exceptional circumstances (e.g., local extinction shortly after discovery).

Transition III: Fire maintenance (Stage 3) to fire-making (Stage 4)

Acquiring the ability to produce fire wherever and whenever one would like is arguably the moment when humans truly transcended the ‘animal’ relationship with fire, a sentiment already expressed previously among the indigenous peoples of the Andaman Islands (Radcliffe-Brown 1922). This ability would have freed hominins from a number of natural constraints with regard to regulating their immediate environment, transforming the environment at large, and altering materials on demand. It is a skill that is unique to our lineage. However, much as it is with the transitions from passive to active fire use and from active fire use to the maintenance and transport of fire, determining approximately when and where hominins developed the technology to produce fire at will has also proven to be problematic.

Indirect evidence of fire-making in the Paleolithic

Given this virtual absence of direct evidence for fire production in the form of fire-making tools from Lower and Middle Paleolithic contexts (discussed further below), researchers have traditionally relied on proxy evidences to infer that early hominins were capable of, and indeed did (at least occasionally), make fire. The regular use of fire by hominins appears to be the most common argument given in favor of the presence of fire production. However, even on this point researchers disagree as to what ‘regular’ means. Roebroeks and Villa (2011a, b) cite the increased presence of fire at Middle Paleolithic archaeological sites after 400-300 ka as sufficient evidence to suggest early Neanderthals were able to make fire. Conversely, Sandgathe and colleagues (2011a, b) point to apparent discontinuities in the fire record, specifically during colder glacial periods when fire would have presumably been of utmost importance, as evidence that Neanderthals did not make fire, but were instead reliant on climate-mediated natural fires to provide the flames they carried back to their habitation sites. They go on to suggest, based on the apparent more systematic occurrence of fire at Upper Paleolithic sites, that modern humans were the first to make fire (Sandgathe et al. 2011b); though, Roebroeks and Villa (2011b) counter this claim by demonstrating that fire use does not appear to be continuous nor ubiquitous at many Upper Paleolithic sites, suggesting Sandgathe et al. are applying a double standard that favors modern humans (cf. Speth 2004).

Others point to advanced pyrotechnologies like the synthesis of birch bark pitch as far back as 250 ka (Koller et al. 2001; Mazza et al. 2006) as tacit evidence for the Neanderthal capacity to produce fire (e.g., Roebroeks and Villa 2011a; Wragg Sykes 2015; Kozowyk et al. 2017; Cnuts et al. 2018), the logic being that if they used pitches as part of their technologies and hence could perform such a complicated task using fire, then they probably did know how to make it. While known Middle Paleolithic examples of birch bark pitch are clearly anthropogenic, it should be noted, however, that under certain conditions it is possible for small amounts of this material to be produced incidentally when using birch wood as fuel (Cnuts et al. 2018; Schmidt et al. 2019). Another line of evidence in this vein, though perhaps less convincing, is the Neanderthal use of fire as an aid for producing wooden tools (Ennos and Chan 2016; Aranguren et al. 2018; Rios-Garaizar et al. 2018).

One could also suggest that the knowledge of and capacity for fire-making should predate the Neanderthal capacity for symbolic or abstract thought, which has been attested to by their collection and use of colourful iron oxides and black manganese dioxides for use as pigment material (Demars 1992; Soressi and d'Errico 2007; Roebroeks et al. 2012; Pitarch Martí and d'Errico 2018; Dayet et al. 2019; Pitarch Martí et al. 2019), having fashioned jewellery (Zilhão et al. 2010; Caron et al. 2011; Hublin et al. 2012; Radovčić et al. 2015; Welker et al. 2016; Hoffmann et al. 2018a) and, as demonstrated recently, their having produced parietal art (Hoffmann et al. 2018b). Moreover, in the latter example, fire was a requisite element in the process of producing this art deep within caves where an artificial light source would have been necessary for the artists to see what they were doing. In a similar instance, at Bruniquel Cave in France, where two large circles were fashioned from hundreds of broken stalagmites, fire was not only needed to venture the 336 m into the cave where these structures were located, but it also appears, based on the 18 combustion zones situated primarily atop the low stalagmite walls themselves, that fire was directly involved in the (possibly ritualistic) activities taking place here (Jaubert et al. 2016). The possible symbolic use of fire by Neanderthals has also been suggested at Des-Cubierta Cave in Spain, where more than 30 horn cores from aurochs (*Bos primigenius*) and bison (*Bison priscus*) and antlers from red deer (*Cervus elaphus*) were placed within at least eleven hearths inside the cave (Baquedano et al. 2016). These, along with the skull of a steppe rhinoceros (*Stephanorhinus hemitoechus*), have been interpreted as hunting trophies, and the presence of the remains of a Neanderthal child in the back of the cave have led to the suggestion that this was some sort of ceremonial gallery. Whether or not one believes this interpretation, the fact remains that the hearths, much like in Bruniquel, do not appear to have served a utilitarian purpose.

From an ecological perspective, having the ability to create fire at will would presumably have had major implications for how hominins altered the landscape, given the potentially far-reaching destructive nature of fire. This phenomenon is known among more recent hunter-gatherers (e.g., Komarek 1967; Jones 1969; Bowman et al. 2011; see Scherjon et al. 2015 for an overview), but remains more elusive for older contexts. Such environmental impacts could potentially serve as another proxy for fire-making, or at least signal more intensive use or fire. A study attempting to identify human disruption of natural fire regimes in south-western France around the Middle-to-Upper Paleolithic transition – when modern humans entered Europe – could not identify an associated change to the fire regime (Daniau et al. 2010), suggesting either earlier Paleolithic groups did not apply fire to the landscape with sufficient intensities to make a noticeable impact, or that early modern human use of fire in the landscape was largely similar to that of Neanderthals, with the fire regime in the research area having already been altered much earlier after its initial colonization by Neanderthals. Kaplan and colleagues

(2016) use computer modelling to suggest modern humans were using fire as a landscape management tool already by the LGM, and indeed, fire-making tools, while still relatively sparse, appear to become more prevalent in the archaeological record around this period (Stapert and Johansen 1999; and see below). There are a number of Holocene examples for hunter-gatherers altering local or regional fire regimes (e.g., Simmons and Innes 1996; Mason 2000; Bos and Urz 2003; Sevink et al. 2018), while the most drastic increases in fire prevalence appearing once agricultural practices arrived to the region in the Neolithic (e.g., Bradshaw et al. 1997; Carcaillet 1998; Snitker 2018). However, by this point, percussive fire-making is already well-attested to (see Roussel 2005 for an overview). The data for large scale analyses of palaeofire regimes may not be fine-grained enough at the moment to weigh in on this matter, smaller scale studies at the regional or local level may be able to shed light on this issue (e.g., Pop et al. 2016).

While some of these various lines of proxy evidences may add credence to the idea that pre-modern humans made fire, they are not definitive in their support. Indeed, the only way to infer fire-making was a technology used by any particular hominin groups is to identify the tools themselves that were used to make fire (Sorensen et al. 2018).

Direct evidence of fire-making in the Paleolithic

Of the eight families of fire starting methods (see Fig. 1), only the stone-on-stone percussion and wood friction methods are known from prehistoric and modern pre-metallic societies, our knowledge of these methods largely confined to ethnographic examples (Hough 1928; Lagercrantz 1954; Perlès 1977; Collina-Girard 1998; Weiner 2003; Roussel 2005). The wood friction method employs one woody element against another using either a rotational motion, as is the case for the various 'drilling' techniques, or a linear motion, as is the case for systems like the fire-plough and the fire-saw, to produce a super-heated powder that ultimately becomes the glowing ember that is used to start a fire. Wood friction fire-making systems are the most prevalent among modern hunter-gatherers, exhibiting a global distribution (see maps in Roussel 2005). This could be at least partially explained by the common occurrence of woody plants in diverse environments making this a common and easily exploitable resource. However, the poor preservation potential of fire-making tools crafted from woody materials significantly reduces their archaeological visibility, and therefore research potential, with only a small handful of wooden artifacts known from Pleistocene contexts (e.g., Movius 1950; Thieme and Veil 1985; Thieme 1997; Allington-Jones 2015; Aranguren et al. 2018; Rios-Garaizar et al. 2018).

The stone-on-stone percussion method generally involves striking a piece of pyrite or marcasite (FeS_2) with a stone 'strike-a-light' of similar or greater hardness (usually flint or another siliceous raw material like quartz or quartzite) to produce sparks that are captured by tinder. Ethnographically, this method has been employed primarily in high latitudes in North and South America, and in Melanesia and Australia (see again the maps in Roussel 2005), and archaeologically throughout Europe (discussed below). The preferred morphology of the strike-a-light tool can be extremely variable between cultures and time periods. This means archaeologists are largely reliant on microwear analysis to identify the tell-tale traces left behind on tools to infer their having been used to make fire (Collin et al. 1991; Beugnier and Pétrequin 1997; Stapert and Johansen 1999; van Gijn et al. 2006; Rots 2012; Guéret 2013; Sorensen et al. 2014, 2018). The typical suite

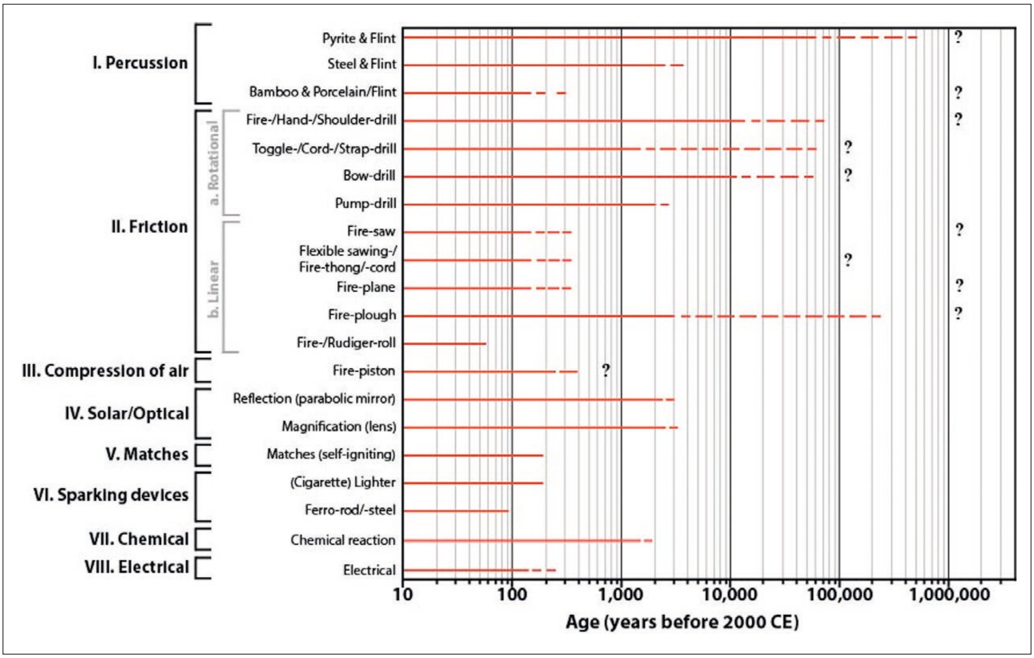

Fig. 1: Chart showing the chronologies of the different families and methods for making fire (following Weiner 2003), with the ages scaled logarithmically for clarity. Solid red lines indicate known instances of the fire-making method, either derived from historical descriptions, ethnographic observations or archaeological findings. Dashed red lines indicate plausible use of a fire-making method based on archaeological proxy data (e.g., the presence of pyrite within an archaeological site) or more ambiguous archaeological finds interpreted as fire-making equipment. Question marks indicate that the materials necessary for executing the method would have been available to hominins and that the gestures required to produce fire were theoretically possible. The positioning of these various chronological indicators are based primarily on data contained in the following sources: percussion, friction and fire-piston methods (Hough 1928; Lagercrantz 1954; Perles 1977; Collina-Girard 1998; Weiner 2003; Roussel 2005; additionally for the bow drill, d'Errico et al. 2012); the fire- or Rudiger-roll (http://www.primitiveways.com/fire_roll.html; last access November 19, 2019); chronological data for the other 'modern' methods of fire-making (Hough 1928; additionally, the early chemical fire dates derive from the advent of 'Greek fire' ca. 672 A.D.; Pryor and Jeffries 2006). See also Kölbl and Conard 2009.

Abb. 1: *Diagramm mit Angabe der zeitlichen Tiefe der verschiedenen Familien und Methoden der Feuerherstellung (nach Weiner 2003); die Altersangaben sind aus Gründen der Deutlichkeit logarithmisch skaliert. Durchgehende rote Linien kennzeichnen entweder aufgrund historischer Beschreibungen, ethnografischer Beobachtungen oder archäologischer Funde belegte Fälle der jeweiligen Feuerherstellungsmethode. Gestrichelte rote Linien kennzeichnen denjenigen Gebrauch einer Feuerherstellungsmethode, der auf Grundlage indirekter archäologischer Hinweise (beispielsweise Vorkommen von Pyrit in einer archäologischen Fundstelle) oder uneindeutig als Ausrüstung zur Feuerherstellung interpretierter archäologischer Funde plausibel erschlossen ist. Fragezeichen deuten an, dass die Materialien, die für die Anwendung dieser Methode notwendig waren, bereits zu dieser Zeit für Menschen verfügbar gewesen und dass die notwendigen Handgriffe theoretisch möglich gewesen wären. Die Platzierung der verschiedenen chronologischen Anzeiger basiert hauptsächlich auf Daten, die in den folgenden Quellen aufgeführt sind: Schlag-, Reibungs- und Kompressions-Methoden (Hough 1928; Lagercrantz 1954; Perles 1977; Collina-Girard 1998; Weiner 2003; Roussel 2005; zusätzlich zum Feuerbohrer: d'Errico et al. 2012); Feuer- oder Rudiger-Rolle (http://www.primitiveways.com/fire_roll.html; letzter Zugriff 19.11.2019); chronologische Daten für die anderen ‚modernen' Methoden der Feuerherstellung (Hough 1928; darüber hinaus beruhen die Daten für frühes chemisches Feuer auf dem Aufkommen des ‚Griechischen Feuers' ca. 672 v.Chr.: Pryor und Jeffries 2006). Siehe auch Kölbl und Conard 2009.*

of traces observed include areas of rounding, crushing and/or microflaking on tool edges or surfaces, often visible with the naked eye or at low magnification, that contain zones of mineral polish and clustered, oriented striations that are visible using high-power microscopy. Compared to wooden fire-making implements, strike-a-lights have greater research potential into the question of early fire-making due to their physical resilience. This is less true for the pyrite element of the stone-on-stone fire-making kit, which is prone to a chemically erosive process called 'pyrite decay' (discussed more extensively in the following section).

Turning now to the archaeological record, percussive fire-making tools are well-attested to among later prehistoric peoples in Europe (see Roussel 2005 for an overview), appearing regularly in Neolithic and Bronze Age deposits (e.g., Close-Brooks et al. 1972; Beugnier and Pétrequin 1997; Stapert and Johansen, 1999; van Gijn et al. 2006; Teather and Chamberlain 2016), and often but to a lesser extent at Mesolithic and late Upper Paleolithic sites (e.g., Stapert and Johansen 1999; Rots 2012; Guéret 2013; Pyżewicz 2015; Osipowicz et al. 2018). However, these tools become increasingly sparse the deeper into the Paleolithic one looks, with most Upper Paleolithic examples coming from post-Last Glacial Maximum contexts (i.e., from the Magdalenian onward; see Table 1 in Sorensen et al. 2014). Prior to this, there is one Gravettian or Protoaurignacian strike-a-light inferred from microwear analysis (Slimak and Plisson 2008), and to my knowledge, there are currently no published findings of Aurignacian strike-a-lights, though there are a number of tools described in the literature that are potentially good candidates based on written descriptions of probable use damage (Bardon et al. 1908; Bouyssonie et al. 1913; Patte 1937; Symens 1988). Upper Paleolithic pyrite specimens are also relatively rare (see Table 2 in Sorensen et al. 2014). Despite this paucity of Upper Paleolithic fire-making tools, there does not appear to be any real controversy surrounding the abilities of the earliest modern humans in Europe to make fire (cf. Sandgathe et al. 2011a, b). I will be looking more deeply into this issue in an upcoming research project.

Prior to my dissertation research, evidence for fire-making in the Middle Paleolithic was virtually non-existent. Sorensen and colleagues (2014) hypothesized that Neanderthal fire-making tools – assuming they exist – must manifest differently than those we know from younger periods (primarily the Neolithic and Bronze Age), otherwise they would likely already have been identified. Given the more expedient nature of Neanderthal stone tool technology (compared to the more formalized and curated tool kits of later Stone Age peoples), I proposed in this article Middle Paleolithic fire-making tools would likely have been short-term, single use items, perhaps used for only one fire-making event. Experiments showed that the traces on these briefly used tools were, as expected, more poorly developed at both the micro- and macro-scales, suggesting these tools would be much more difficult to identify, especially within large lithic assemblages. This was borne out among the numerous archaeological lithic collections scanned for this study in an effort to identify expedient fire-making tools based on my experimental findings, with no promising strike-a-lights having been identified.

The difficulties associated with identifying strike-a-lights among the thousands of lithic artifacts generated within flake-based industries are due to the sheer number of artifacts contained within many of these assemblages. Given the variability in gestures one could employ to make fire using the stone-on-stone method, any suitable artifact could potentially have been used as a strike-a-light. This is a problem that can only be solved through countless hours of 'looking' by knowledgeable and diligent lithic and microwear analysts. A possible strike-a-light with weakly developed traces identified at Bettencourt in northern France dating to 85-75 ka (Rots 2011, 2015; Sorensen and Rots 2014) demonstrates that, despite the inherent difficulties in identifying expedient strike-a-lights, these tools are still recognizable in flake-based Mousterian industries and will likely be identified more often once analysts make a more concerted effort to seek them out.

In a more recent study (Sorensen et al. 2018), we explored an alternative facet of the expedient strike-a-light model described by Sorensen and colleagues (2014) that suggests curated tools found in some Mousterian industries might be more fruitful hunting grounds for fire-making traces, given their multi-purpose nature and longer use-lives compared with simple flake tools. Focus was placed on large bifacial tools recovered from Mousterian of Acheulean Tradition (or MTA) contexts that possess unidentified mineral microwear traces (Claud 2008, 2012; Soressi et al. 2008). We observed that these traces always occur on the interior faces of the bifaces, with the associated striations – and in some instances C-shaped percussion marks – nearly always oriented parallel to the longitudinal axis of the tools, together suggesting a consistent application of oblique percussive force. Very similar traces were produced in fire-making experiments using the flaked 'flat' sides of a biface as a percussive surface against which a fragment of pyrite was struck, readily producing showers of sparks that were easily captured in tinder material to produce a glowing ember. These inferred fire-making traces have so far been observed on dozens of French MTA bifaces, suggesting 1) fire-making was a known use for these tools (i.e., not necessarily an expedient task), and 2) the use of these tools for this function was (at least) a regional techno-cultural phenomenon in France during the late Middle Paleolithic. If this interpretation is correct, then this study provides the first definitive proof of regular fire-making by pre-modern humans.

Another discovery lending tacit support to the idea that Neanderthals could make fire was made by Heyes and colleagues (2016), who found that adding powdered manganese dioxide (MnO_2) to wood turnings reduced the temperature required for combustion of this material by around 100° C, suggesting the addition of MnO_2 to tinder material would aid in fire-making. Numerous of fragments of MnO_2 have been recovered from Middle Paleolithic archaeological layers (Demars 1992; Pitarch Martí and d'Errico 2018; Dayet et al. 2019; Pitarch Martí et al. 2019), many exhibiting traces of grinding for the purpose of producing powder. While this practice has often been attributed to pigment production for decorative or symbolic purposes (e.g., Soressi and d'Errico 2007), use as a tinder enhancer is an intriguing alternative application. In a forthcoming article, I test this hypothesis in a series of actualistic fire-making experiments wherein I find that the addition of MnO_2 powder indeed improves the ability of tinder material to capture sparks produced using the flint-and-pyrite fire-making method (Sorensen in press).

These findings are almost certainly not the final word on this subject. The identification of probable strike-a-light microwear traces on numerous Middle Paleolithic bifaces, as described above, provides perhaps a more promising point of departure than the systematic analysis of whole lithic assemblages described by Sorensen and colleagues (2014). Similarly curated chipped-stone tools found within some stone tool industries provide focal points to which special attention should be paid for seeking out potential evidence for use as fire makers. The longer use-lives of these curated tools (Geneste 1985; Soressi 2002, 2004), coupled with their tendency to be well-travelled and used for multiple tasks (Soressi and Hays 2003; Claud 2008), increases the probability that these tools may have been used at some point, however briefly, to make fire. Thus, applying the methods and knowledge gained in previous research (Sorensen et al. 2014, 2018) to older lithic industries with curated tools like the Quina Mousterian (Middle Paleolithic) and the Acheulean (Lower Paleolithic) could potentially push back the earliest evidence for fire-making by hominin groups deeper into the Paleolithic. And indeed, the use of the flat, flaked surfaces of both Quina scrapers (Beyries and Walter 1996) and Acheulean hand axes (see Table 1 in Claud 2008 and the sources therein) for frictional and percussive activities involving other mineral materials (e.g., pigment grinding and flint knapping) places fire-making well within the realm of possible uses for these tools.

The pyrite problem

Given that pyrite is a necessary element within the stone-on-stone fire-making system, its importance with regard to identifying this method archaeologically cannot be understated. Among modern hunter-gatherers in Tierra del Fuego, pyrite was a curated and exchanged item (Roussel 2005). Save for some important locales like the Cretaceous chalk cliffs along the coast of Normandy and the east coast of England, the relative rarity of pyrite in the northwest European landscape may have made this resource an important item of exchange between Paleolithic groups, making its presence at Paleolithic archaeological sites all the more significant. Indeed, a number of the archaeological pyrite specimens from this period appear to have been carried upwards of 30-90 km to where they were ultimately deposited (e.g., Hayden 1993; Bonjean, personal communication), giving an indication of the importance to this resource to Neanderthals. The collection of extra pyrite nodules or crystals from such locales and the possible subsequent caching of these items within protected caves could, along with taphonomic variables, partially account for the majority presence of unused allochthonous pyrite specimens within some Middle Paleolithic sites. If the iron oxide cortex of a pyrite nodule is left intact, the reactive pyritic interior is largely protected from the destructive ‘pyrite decay’ process.

Pyrite decay occurs when pyrite or marcasite (especially fine-grained species) interacts with the humidity in the air causing a self-perpetuating chemical reaction that breaks down the specimen into various sulphate minerals, sulphur dioxide and sulphuric acid, ultimately potentially causing the complete degradation of the mineral (Larkin 2011; Leduc et al. 2012). However, in depositional environments with higher pH levels (e.g., karstic systems, or perhaps in loess), it is possible for pyrite to re-mineralize in situ to iron oxide (i.e., hematite and/or goethite) (Leduc et al. 2012), as is demonstrated by the remineralized iron oxide cortex that is often present on the outside of pyrite nodules formed in chalk/limestone, as well as on the surface of the anthropogenic groove created on the Magdalenian Trou de Chaleaux pyrite nodule, presumably from use for making fire (see Fig. 3 in Sorensen et al. 2014). The preservation potential for pieces (and their associated use traces) undergoing such a remineralization process would be much greater than those undergoing the pyrite decay reaction series. Therefore, barring these special depositional settings, it is unlikely for nodular fragments to preserve when exposed to the elements. On the other hand, if pieces of pyrite were curated items due to their relative rarity, it is likely that they would have been used until they were completely exhausted, again limiting their archaeological visibility.

The use traces potentially imparted onto experimental pyrite fragments while producing sparks are described by Sorensen and colleagues (2014), and usually appear as artificially flattened or concave surfaces (see also Beugnier and Pétrequin 1997). Perhaps more important, however, are the 'abraded' surfaces incidentally created along the edges of broken pyrite nodule fragments on the iron oxide cortex that often encases these nodules. Given the tendency for the interior pyritic material to degrade when exposed to the air, in instances where only the exterior cortical fragments are preserved (such as at Scladina Cave, see Bonjean et al. 2011), these faceted, seemingly ground surfaces could be mistaken as evidence for pigment processing rather than resulting from fire-making.

Furthermore, ethnographic accounts from a number of North American native tribes detail the use of two pieces of pyrite being struck together to make fire (see Hough 1928 and the sources therein). Such a method not only precludes the need for a flint strike-a-light tool, but it would also lead to battering/wear traces on the pyrite fragments that are potentially quite different from traces left behind by flint artifacts (personal observation, unpublished experiments). If this method was regularly used during the Paleolithic, it could provide yet another reason for the presence of so few flint strike-a-light tools, but could, for example, also account for the more hammer stone-like distribution of battering traces present on the exterior portion of the Aurignacian Vogelherd pyrite nodule (Weiner and Floss 2004). Unfortunately, it is ultimately the potential ambiguity of use traces on pyrite specimens – or a complete lack thereof, as is more often the case – that makes it difficult to rely solely on the presence of pyrite at Paleolithic archaeological sites as proof-positive indicators of fire-making. Nevertheless, the recovery of pyrite at a Paleolithic site could indicate a higher probability for the presence of strike-a-light tools within the lithic assemblage, thus helping to guide future analysis.

Finally, while the microwear evidence presented by Sorensen and colleagues (2018) make a good case for fire production by Neanderthals, these interpretations could be further strengthened through the identification of pyritic residues in close association with the observed strike-a-light microwear traces. A scanning electron microscope (SEM) coupled with a spectrometer has been used in such a fashion to identify minute mineral particles containing iron and sulphur atoms on the surfaces of a few late Upper Paleolithic tools interpreted as strike-a-lights (Stapert and Johansen 1999). Two more studies have employed various other analytical techniques to chemically identify readily visible pyritic residues on Neolithic and Bronze Age tools interpreted as strike-a-lights, including micro-X-ray fluorescence (µ-XRF), micro-X-ray diffraction (µ-XRD), RAMAN spectroscopy, and SEM coupled with energy-dispersive analysis of X-rays (EDAX) (Pawlik 2004; Lombardo et al. 2016). However, since no pyritic residues were observed on the MTA bifaces, the usefulness of these particular methods as prospection tools for detecting optically-invisible pyritic micro-residues is currently being explored.

Final Thoughts on the Origins of Fire-Making

There are numerous lingering questions surrounding the need for hominins to incorporate fire-making technology into their day-to-day lives. The prevailing logic that 'necessity is the mother of invention' suggests that external stimuli requiring adaptive solutions are required for innovation. Was this also the case for fire-making? Given the deep time depth of archaeological evidence for fire use, was there a point at which human reliance on fire became so great that a change in conditions would necessitate a technological response? What would these conditions be? One might expect a late onset of fire-making in warmer regions or zones with active volcanism where natural fires were a regular feature in the landscape. However, if the need for cooked food was the primary driver of hominin fire use, reduced access to natural fires in a normally fire-prone environment (like in large parts of Africa or in Australia) might stimulate hominins to begin making fire for themselves. Alternatively, a shift towards cooler climate (presumably in Eurasia) may have driven hominins to adopt fire-making as a necessary thermoregulatory tool, or increased hunting of large animal species may have fostered the need for fire for food processing. It seems unlikely that hominins would have developed fire-making technology expressly for the purpose of range expansion, but that range expansion was later facilitated by this technical knowledge. However, it is entirely possible that the most ancient forms of fire-making (i.e., stone-on-stone percussion and wood-on-wood friction) were both simply accidental innovations that were, nevertheless, instantly adopted due to their inherent usefulness, regardless of conditions. Under this scenario, fire-making could have come about at virtually any point in prehistory, anywhere humans were present, and likely multiple times (at least early on) since it is entirely plausible that this knowledge was occasionally lost in localized extinction events (especially in peripheral areas) prior to fire-making becoming 'fixed' in the collective knowledge of one or more human meta-populations (Oakley 1961). This 'messiness' helps to highlight the importance of identifying fire-making tools in the archaeological record. But unless these tools are identified, we are still largely reliant on proxy evidence for fire-making to answer questions regarding the early origins of fire-making.

Wood-on-wood friction versus stone-on-stone percussion

There is still uncertainty as to whether wood-friction or stone-on-stone percussion was the first fire-making system (Hough 1926, 1928; Watson 1939; Weiner 2003). Many researchers tend to believe that the analogous nature of the stone-on-stone method to flint knapping suggests this was likely the earliest method for fire production (Watson 1939; Oakley 1961; Weiner 2003). Conversely, the simple act of rubbing one's hands together to warm up may have helped hominins make the connection between friction and heat. This could then have been extrapolated to friction between other materials like wood, with the close association between wood and fire potentially evoking the idea that fire was contained within the wood (comparable to 18th Century theory of 'phlogiston' introduced by Johann Joachim Becher and formalized by Georg Ernst Stahl; Blumenthal and Ladyman 2017). Simply noticing the heat produced while sharpening spears or digging sticks against a stone could have further developed the idea that fire might be produced from rubbing wood. Friction fire-making, however, requires very deliberate, rapid and sustained force to produce enough heat to create the super-heated wood powder that becomes a glowing ember. Some researchers believe this technology (specifically the fire-drill) may not have been introduced until later periods – perhaps the late Middle Stone Age (MSA) or Later Stone Age (LSA) in Africa (Collina-Girard 1993; Ambrose 1998; McBrearty and Brooks 2000; Thompson et al. 2004; Orton 2008; Werner and Willoughby 2018) and/or during the UP in Eurasia (Pitarch Martí et al. 2017; Wei et al. 2017) – in parallel with analogous evidence of drilling technology (Hough 1926, 1928; Oakley 1961; Kidder 1994).

Pointing to the ethnographic record, others go on to argue that the more localized distributions of other variants of the wood friction method like the fire-saw, fire-plough and flexible fire-thong (primarily in Southeast Asia) could indicate later origins (Lagercrantz 1954; Roussel 2005). However, given the parallel described above between the motion required to sharpen wooden tools and the fire-plough method (Fig. 2), this could have much deeper origins, only to have been superseded by the fire-drilling method much later on. Indeed, it has been suggested that a piece of carbonized wood from Kalambo Falls in Zambia exhibiting curious grooves could represent an early example of the fire-plough (Oakley 1961; Leroi-Gourhan 1994). Ultimately, the relatively poor preservation of wood in the archaeological record creates a classic 'absence of evidence' conundrum. Nevertheless, there have been a number of Pleistocene wooden tool finds recovered from special depositional contexts (Movius 1950; Thieme and Veil 1985; Carbonell and Castro-Curel 1992; Thieme 1997; Allington-Jones 2015; Aranguren et al. 2018; Rios-Garaizar et al. 2018), and these provide some hope that wooden fire-making tools from this period may yet be discovered, assuming they were used. There are a few instances of artifacts having been interpreted as fire-making equipment coming from Middle and Upper Paleolithic deposits (see Collina-Girard 1993, 1998), like the purported Krapina

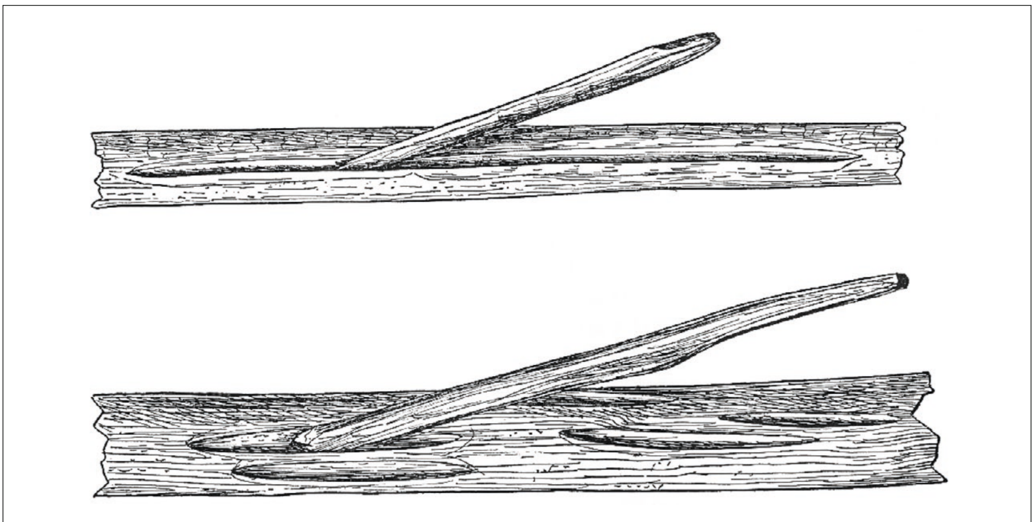

Fig. 2: Ethnographic fire-ploughs from Tuamotu Islands (upper) and Jaluit (lower) (after Lagercrantz 1954).

Abb. 2: *Ethnografische Feuerpflüge von den Tuamotu Inseln (oben) und dem Jaluit Atoll (unten) (nach Lagercrantz 1954).*

fire drill (Gorjanovic-Kramberger 1910). However, these are considered dubious, at best, while examples of hearth boards – considered the more diagnostic element of a fire-drill friction fire-making set – are only known from Holocene deposits, and most of these occur outside Europe (see Davies 1975; Collina-Girard 1993, 1998; Roussel 2005 and sources therein).

Percussive fire-making using flint and pyrite is all but unknown from Africa, both ethnographically and archaeologically, with the adoption of flint and steel percussive fire-making only making an appearance on the continent after being introduced by European colonists (see Lagercrantz 1954; Roussel 2005, and notes). This could be partially due to the apparent paucity of pyrite-bearing rock outcrops in Africa, though my knowledge of this fact is admittedly limited; or if present, the poor preservation of pyrite due to the warmer climate would have likely caused specimens to quickly decay once exposed to the air, limiting their usefulness at the time, and ultimately reducing their archaeological visibility. While pyrite has been recovered from an Iron Age site in Iran, presumably for use in fire-making (Overlaet 2008), I have not come upon any archaeological literature mentioning the presence of pyrite at any Middle Eastern Stone Age sites, nor in the Levant despite the presence of pyrite nodule-bearing outcrops in southern Israel (Sass et al. 1965). Nevertheless, regular fire use appears to have been a relatively early phenomenon in the Levant (e.g., Karkanas et al. 2007; Alperson-Afil 2008; Meignen et al. 2009; Friesem et al. 2014; Shahack-Gross et al. 2014). Might the increase in fire proxies at Tabun Cave around 300 ka (Shimelmitz et al. 2014), for example, possibly relate to the introduction of fire-making technology? Or, could this apparent increase in fire evidence at the site be more related to an increase in natural fire activity in the region, or perhaps to any of the various environmental or other cultural factors highlighted by Sorensen (2017) and Sorensen and Scherjon (2018)? While it is yet difficult to say for sure what caused the increase in fire presence at this site during this period, what is certain is that to date, no strike-a-lights nor pyrite fragments have been recovered from Tabun Cave (Shimelmitz, personal communication).

The question of whether the wood friction or stone percussion method came first is perhaps less important than *when* fire-making technology in general was first developed. Only future discoveries of preserved fire-making equipment will bring us closer to discerning this moment in prehistory. It could be that simple stick sharpening led initially to the development of the fire-plough method very early on, possibly predating other wood friction methods like the fire-drill. Based on the geographic distributions of both ethnographic and known prehistoric wooden fire-making equipment (see Lagercrantz 1954; Roussel 2005), it is possible to speculate that the fire-drilling method may have had later African origins among anatomically modern humans, perhaps being introduced as early as the late MSA or LSA, and was then carried out of Africa into Eurasia. The paucity of evidence for rotational drilling technology in Eurasian Middle Paleolithic assemblages could indicate that Neanderthals likely did not employ the fire-drilling technique, but the fire-plough method may have been employed, though evidence for this method is also currently lacking. Conversely, the stone percussion fire-making method was possibly a European (or Eurasian) innovation, perhaps initially introduced by (early?) Neanderthals (Sorensen and Rots 2014; Rots, 2015; Sorensen et al. 2018) and then later adopted by anatomically modern humans arriving from Africa, either through independent invention, or possibly through cultural diffusion from Neanderthals (as has been proposed for leather working tools called *lissoirs*, these first making a limited appearance in Middle Paleolithic deposits and then proliferating during the Upper Paleolithic; Soressi et al. 2013). The time necessary for this technology to proliferate among these initial groups of modern humans moving into Europe could potentially explain the apparent infrequent occurrence of percussive fire-making tools in the early Upper Paleolithic.

Conclusion

Questions clearly still remain regarding fire use and the possibilities for fire-making among Paleolithic peoples. Indeed, the subject will likely remain contentious, as recent publications have shown (see Dibble et al. 2017, 2018b). The purpose of my research has not been to put an end to the fire debate, but instead to push the envelope of what we know about the pyrotechnic capabilities of our closest hominin relatives, the Neanderthals, and to provide food for thought for continued discussion on this heated topic. Understanding better how fire-affected artifact assemblages are produced will naturally lead to an improvement in how we interpret archaeological fire proxy data. The resultant more nuanced view of anthropogenic fire traces, while not necessarily providing direct evidence of fire-making, should provide researchers with a better framework with which to identify the signatures of fire-making in the archaeological record. This, in turn, will not only indicate where and from which periods one could expect to find fire-making tools, thus highlighting 'high probability' archaeological assemblages for analysis, but will also provide added validity to any possible fire-making tools that are identified in these contexts. As it currently stands, the relative scarcity of fire-making tools in the Paleolithic record, whether real or a result of a lack of looking or recognition, creates a sense that this technology may have not been critically important to pre-modern human groups. However, recent studies presenting probable fire-making tools from European Middle Paleolithic contexts (Sorensen and Rots 2014; Sorensen et al. 2014; 2018; Rots 2015) provide not only the analytical tools necessary to recognize these implements when encountered, but also optimism that more will be identified from yet older contexts in the future.

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