Beyond prometheus: pursuing the origins of fire production among early humans

Sorensen, A.C.

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Issue Date: 2018-12-13

1. Introduction

Thus Zeus spoke in rage… and would not bestow the power of inexhaustible fire to the Melian tribe of mortal men who dwell on the earth. However, the noble son of Iapetos deceived him, pilfering the far-seen glow of inexhaustible fire in a hollow wand of fennel. And he stung high-thundering Zeus to the depths of his soul whose dear heart was filled with rage as he glimpsed amongst men the far-seen glow of fire. (Hesiod, Theogony: 561–569)

Whether obtained from Prometheus via the heavens in the form of lightning, or perhaps collected directly from the volcanic forges of Hephaestus, the human acquisition of fire set our hominin ancestors on a trajectory that would in the end culminate in a society today just as dependent on fire, if not more so, than it was long ago amongst early hunter-gatherers. 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).

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 behaviour 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 (Gowlett, 2006; Oakley, 1956; Rolland, 2004; Weiner, et al., 1998; but see Perles, 1977; Roebroeks and Villa, 2011a). Since fire can act as a deterrent of dangerous predators (Brain and Sillen, 1988; Goudsblom, 1986), 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 Gowlett, 2014; Dunbar and Shultz, 2007; Wiessner, 2014) that fostered an environment ripe for cultural and technological advances. Regarding the latter, fire improved the workability of wooden (Aranguren, et al., 2018; Ennos and Chan, 2016; 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, et al., 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; Fonseca-Azevedo and

Herculano-Houzel, 2012; Organ, et al., 2011; 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, 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 the research proposed here is 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 (Berna, et al., 2012; Roebroeks and Villa, 2011a; Wrangham, 2009), as unfortunately for archaeologists, fire production has been notoriously difficult to identify in the archaeological record prior to the Holocene (see Chapter 4).

As pointed out in a recent publication by Sandgathe and Berna (2017), the subject of Palaeolithic 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 behavioural 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? The research conducted for this dissertation concerns itself principally with the final two questions, these focusing more on the latter stages of humankind's love affair with fire. The purpose of this research, therefore, is two-fold: 1) to determine from the archaeological record how and to what extent Neandertals used fire, and 2) to identify artefactual evidence of fire making by these peoples. The first portion of this chapter presents an extensive overview of the research history of human/fire interactions and the means by which researchers attempt to identify transitions to more advanced stages of hominin fire use. The latter section provides a description of the four peer-reviewed papers that comprise the core of the dissertation and the research goals of each.

1.1 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 a in many environments a common occurrence, 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, take advantage of recently burned tracts of land for grazing or foraging, or are attracted to smoke and actively interact with burning fires (Komarek, 1969), including some primate species (Parker, et al., 2016; Pruetz and Herzog, 2017; Pruetz and LaDuke, 2010). 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 Burton, 2009; Chazan, 2017; Frazer, 1930; Goudsblom, 1986; Parker, et al., 2016; Pruetz and LaDuke, 2010), 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 travel, and 3) decreased threat of predation. The burning away of grassy vegetation allows for easier acquisition of hidden fruits, seed or tubers, while also leaving behind lightly cooked small vertebrate and invertebrate species (Sponheimer, et al., 2005a, 2005b), the latter potentially leading to increased insectivory among some groups (Bogart and Pruetz, 2011; Burton, 2009; 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 active use of fire (Stage 2). Actively using fire may have been limited at first, with hominins actively feeding a 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 build it anew and maintain it in another location for a period of time. 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 later 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 realised or when techniques for producing fire were identified, they were not 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.

1.1.1 Transition I: Nature fire habituation (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, 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.

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, but also for carrying fire from one place to another (Medler, 2011).

Despite these possible fire-forged shifts in early hominin physiology, as was alluded to above, 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 Palaeolithic sites containing evidence for fire use, usually in the form of localised patches of thermally altered sediments, lithic artefacts 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) and Chesowanja (Gowlett, et al., 1981, 1982; Isaac, 1982), and Gadeb in Ethiopia (Barbetti, 1986; Barbetti, et al., 1980; Clark and Kurashina, 1979), with slightly later occurrences in South Africa around 1.0 Ma at Swartkrans (Brain, 1993; Brain and Sillen, 1988; 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 evinced by 'phantom hearths' comprised of clusters of heated lithic artefacts and small carbonised plant remains (Alperson-Afil, 2008; Alperson-Afil and Goren-Inbar, 2006; Alperson-Afil, et al., 2007), 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 (Binford and Ho, 1985; Gao, et al., 2017; Wu, 1999; Black, 1932; Goldberg, et al., 2001; Weiner, et al., 1998).

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 (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 of which 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).

1.1.2 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 that it affords, likely increasing the regularity with which they would have used fire. 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 Neandertals to conserve and transport their fire is difficult say at the moment. Among the earliest sites from this transitional period exhibiting single or multiple combustion zones or hearths are Vérteszöllös in Hungary (Vértes and Dobosi, 1990), Terra Amata in southern France (Villa, 1982, 1983), Menez-Dregan in northwest France (Monnier, et al., 2016; however, see Mercier, et al., 2004, who date the Menez-Dregan deposits to MIS 7) 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 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, 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 (Daujeard and Moncel, 2010; Moncel, et al., 2008), 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 Palaeolithic Israeli sites exhibiting stacked central hearth features/combustion areas, the earliest example appearing at Qesem Cave 400–300 ka (Blasco, et al., 2016; Karkanas, et al., 2007; Shahack-Gross, et al., 2014), and a bit later at Tabun (Jelinek, et al., 1973; Shimelmitz, et al., 2014), Kebara (Albert, et al., 2012; Meignen, et al., 2008; Schiegl, et al., 1996; Speth, 2006) and Hayonim caves (Goldberg, 1979; Meignen, et al., 2008; Schiegl, et al., 1996), and 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 Neandertal 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 Palaeolithic sites with fire evidence, see Dataset S1 in Roebroeks and Villa, 2011a). Included among the sites with well-preserved evidence for recurrent fire use by Neandertals are, for example, Abric Romaní (Carbonell 2012, and papers therein; Courty, et al., 2012; Vallverdú, et al., 2012; Vaquero, et al., 2001) 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., 2018a, and papers contained therein; Dibble, et al., 2009; Sandgathe, et al., 2011a; Turq, et al., 2011), Roc de Marsal (Aldeias, et al., 2012; Goldberg, et al., 2012; Sandgathe, et al., 2011a), Combe Grenal (Binford, 2007; Bordes, 1955, 1972) 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), Biśnik Cave in Poland (Cyrek, et al., 2014, 2016). As the list above demonstrates, well-stratified sites with fire evidence 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 (Carciumaru, 1999; Mertens, 1996; Pàunescu, 1993), Ksiecia Jozefa in Poland (Zieba, et al., 2008, 2010) and Starosele in Crimea (Demidenko, 1998; Formosov, 1958; Marks, et al., 1998).

It is entirely possible that the diachronic trend of increasing fire evidence 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 (Sandgathe, et al., 2011b; Surovell and Brantingham, 2007). Moreover, the increased frequency of fire remains at archaeological sites over the course of the Middle Palaeolithic does not necessarily mean that fire was used constantly by Neandertals, and hence should at some point become a ubiquitous feature at all Neandertal sites. And indeed, it is not. This apparent variability in fire use could be related to any number of causes (discussed in greater detail in Chapter 2). It could simply be a factor of taphonomy, with fire remains preserving differentially between sites or climatic periods. This idea appears to find support in another paper by Surovell and colleagues (2009), somewhat contradicting the previous claims made by these authors. 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.

Other researchers point to various cultural responses to changes in climate as the driving force behind variability in Neandertal fire use. In an effort to explain the weaker fire signals observed in archaeological layers deposited under glacial conditions at the French sites of Pech de l'Azé IV and Roc de Marsal, it has been proposed that Neandertals, lacking the ability to make fire, were thus reliant on harvesting flames for their hearths from natural fires ignited by lightning strikes, these being less prevalent during colder climatic conditions (Dibble, et al., 2017, 2018b; Sandgathe, et al., 2011a; 2011b). However, fire use may have also been a matter of choice, where, in certain situations, Neandertals chose to use or not use fire based on the costs and benefits using fire would entail (Henry, et al., in press). A scenario where this could have been a factor is during colder climatic conditions when woody fuel (i.e. trees) was less prevalent in the environment, leading both to greater fuel economisation and preferential location of camps and habitation sites nearer to fuel sources (cf. Binford, 1978). Boiling food in perishable containers (e.g. animal paunches, bladders or hides, or possibly birch bark containers) would have required less fuel and smaller fires than stone-boiling or roasting (Speth, 2012; Speth, 2015), thereby reducing the intensity of fire use (and the resultant archaeological fire signals; see Chapters 2 and 3). 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 such conditions (Carmody, et al., 2011; Carmody and Wrangham, 2009; Castel, et al., 2017; Glover, et al., 1977; Heaton, et al., 1988; Speth, 2017; Zink and Lieberman, 2016; Zink, et al., 2014), 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 (Aiello and Wheeler, 2003; Chevalier, et al., 2015; Hammel, et al., 1959; Scholander, et al., 1958a, 1958b; Steegmann, et al., 2002), 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 Churchill, 2014; Hosfield, 2016; MacDonald, 2018; White, 2006). 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. It has also been suggested that Neandertals 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. Thus, once having acquired the ability to make fire, it is unlikely that this exceptionally useful tool would simply have been forgotten by Neandertal groups, barring very exceptional circumstances.

1.1.3 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 took major step out of the realm of animals' relationships with fires. 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.

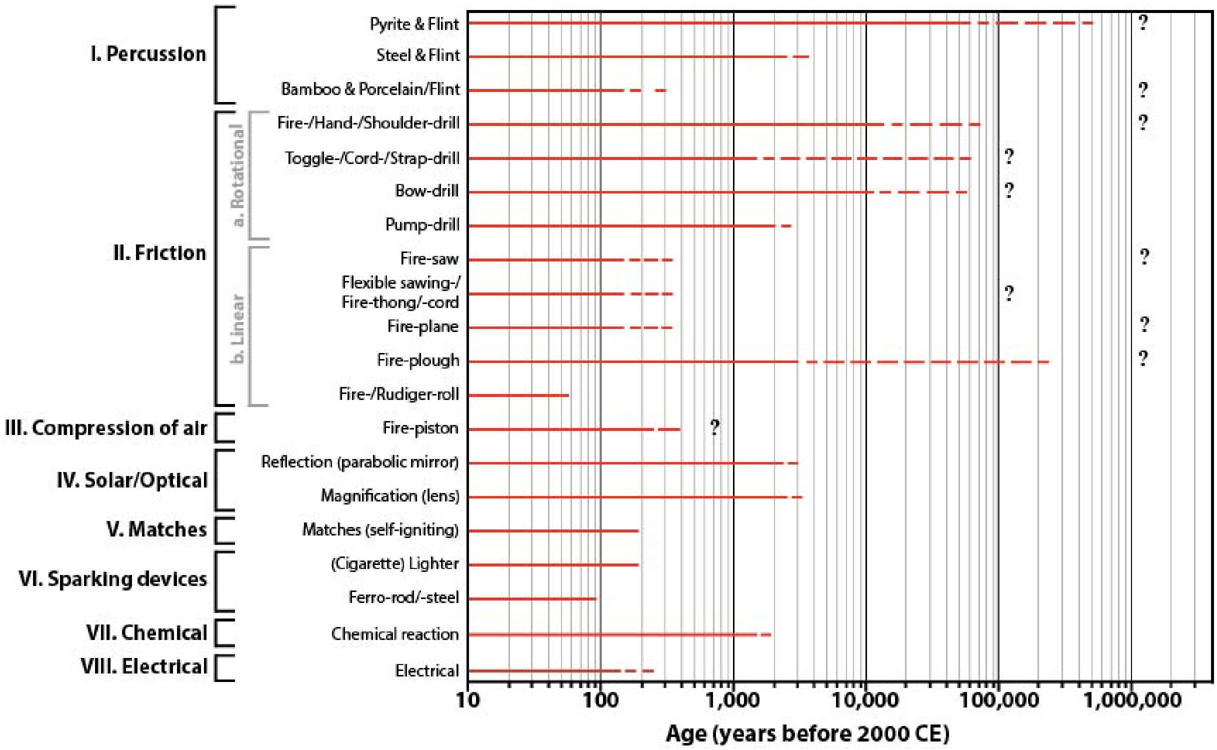

Figure 1. Chart showing the chronologies of the different families and methods for making fire (following Weiner, 2003), with the ages scaled logarithmically for clarity. Solid red lines indicate known instances of the fire making method, either derived from historical descriptions, ethnographic observations 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 (Collina-Girard, 1998; Hough, 1928; Lagercrantz, 1954; Perles, 1977; Roussel, 2005; Weiner, 2003), additionally for the bow drill (d'Errico, et al., 2012) and the fire- or Rudiger-roll (http://www.primitiveways.com/fire_roll.html); chronological data for the other 'modern' methods of fire making were acquired from the Wikipedia pages discussing the named methods or technologies (note: the chemical fire dates derive from the 'Greek fire' page). See also Kölbl and Conard, 2009.

Of the eight families of fire starting methods (see Fig. 1), only the percussion and friction methods are known from prehistoric and modern pre-metallic societies (e.g. Weiner, 2003); though, both the solar and perhaps the compression technologies would have been possible to produce with Stone Age tools and materials. From an archaeological perspective, both the percussion and friction methods have their respective advantages and disadvantages (this is discussed in greater detail in Chapters 4 and 6). While woody plants are generally more prevalent in the environment and thus more easily exploitable, the preservation potential of tools crafted from these materials is very low, with only a small handful of such artefacts known from Pleistocene contexts (e.g. Allington-Jones, 2015; Aranguren, et al., 2018; Movius Jr, 1950; Rios-Garaizar, et al., 2018; Thieme, 1997; Thieme and Veil, 1985). The percussive method using flint in conjunction with iron sulphide minerals (i.e. pyrite and marcasite), on the other hand, utilises techniques intimately familiar to hominins (e.g. stone knapping and other pounding activities), using materials that are much more robust and more apt to preserve archaeologically. This latter point applies more to the flint 'strike-a-light' element of the stone-on-stone fire making kit since iron sulphide minerals are prone to a chemically erosive process called 'pyrite decay'. Pyrite decay occurs when the mineral (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 causing the complete degradation of the mineral, assuming the process is not halted (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-mineralise in situ to iron oxide (i.e. hematite and/or goethite) (Leduc, et al., 2012), as is often the case for the iron oxide cortex on the outside of pyrite nodules, 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 Chapter 4). The preservation potential for pieces (and their associated use traces) undergoing such a remineralisation process would be much greater than those undergoing the pyrite decay reaction series.

Save for a dozen or so other Middle Palaeolithic pyrite finds (and perhaps around two dozen pyrite finds from the whole of the Upper Palaeolithic) suggesting a plausible use of percussive fire making technology, according to published findings, fire making tools (i.e. flint strike-a-lights) do not really appear in Europe (or elsewhere, for that matter) until the arrival of the Upper Palaeolithic Magdalenian culture after the Last Glacial Maximum (MIS 2) (discussed in more detail in Chapter 4). Given this virtual absence of direct evidence for fire production in the form of fire making tools from Lower and Middle Palaeolithic contexts (discussed further below and in Chapter 4), 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 favour of the presence of fire production. However, even on this point researchers disagree as to what 'regular' means. Roebroeks and Villa (2011a, 2011b) suggest the increased presence of fire at Middle Palaeolithic archaeological sites after 400–300 ka as sufficient evidence to suggest early Neandertals were able to make fire, this point perhaps supported—albeit weakly—by the oldest known archaeological instance of a pyrite nodule appearing around this time at Menez-Dregan (Monnier and Hallegouet, 2004). Conversely, Sandgathe and colleagues (2011a, 2011b) 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 Neandertals 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 Palaeolithic 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 Palaeolithic sites, suggesting Sandgathe et al. are applying a double standard that favours modern humans (cf. Speth, 2004).

While the benefits of fire making are easily relatable at the personal or species levels, given the potentially far-reaching destructive nature of fire, having the ability to create fire at will has major implications for how hominins can potentially alter the landscape. This phenomenon is known among more recent hunter-gatherers (e.g. Bowman, et al., 2011; Jones, 1969; Komarek, 1967; Scherjon, et al., 2015), but remains more elusive for older contexts. Such environmental impacts could potentially serve as another proxy for fire making, or in a similar vein as the above paragraph, 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 Palaeolithic transition—when modern humans entered Europe—could not identify an associated change to the fire regime (Daniau, et al., 2010), suggesting either earlier Palaeolithic 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 Neandertals, with the fire regime in the research area already having been altered much earlier after its initial colonisation by Neandertals. Kaplan and colleagues (2016) suggest this may have also been the case around the LGM, and indeed, fire making tools, while still relatively sparse, begin to become more prevalent in the archaeological record around this period (Stapert and Johansen, 1999). There are a number of Holocene examples for hunter-gatherers altering local or regional fire regimes (e.g. Bos and Urz, 2003; Mason, 2000; Sevink, et al., 2018; Simmons and Innes, 1996), 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). By this point, percussive fire making is well-attested to (see Roussel, 2005 for an overview).

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 Neandertal capacity to produce fire (e.g. Cnuts, et al., 2017; Kozowyk, et al., 2017; Roebroeks and Villa, 2011a; Wragg Sykes, 2015), 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 Palaeolithic 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., 2017).Another line of evidence in this vein, though perhaps less convincing, is the Neanderthal use of fire as an aid for producing wooden tools (Aranguren, et al., 2018; Ennos and Chan, 2016; Rios-Garaizar, et al., 2018).

One could also suggest that the knowledge of and capacity for fire making should predate their capacity for symbolic or abstract thought, which has been attested to by their collection and use of colourful iron oxides and black manganese dioxides as pigment material (Demars, 1992; Martí and d'Errico, 2018; Roebroeks, et al., 2012; Soressi and D'Errico, 2007), having fashioned jewellery (Caron, et al., 2011; Hoffmann, et al., 2018a; Hublin, et al., 2012; Radovčić, et al., 2015; Welker, et al., 2016; Zilhão, et al., 2010) 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 activities taking place here (Jaubert, et al., 2016). The possible symbolic use of fire by Neandertals 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 Neandertal 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.

While these proxy evidences may indeed be valid, they are not definitive in their support for fire making during the Middle Palaeolithic. This study starts from the proposition that the only way to infer fire making is to identify the tools themselves that were used to make fire.

2.1 Research Questions and Outline of Thesis Chapters

The primary goal of the research project described in this dissertation is to try to determine when in the course of humankind our ancestors became proficient producers of fire. While this overarching question of 'When?' potentially opens up the whole of human prehistory to scrutiny—and rightly so!—one must begin the search somewhere. Fire making is a known phenomenon among prehistoric modern humans, and the evidence, while limited, does suggest Upper Palaeolithic modern humans living in Europe from mid-MIS 3 onward were indeed able to produce fire, though this evidence becomes more and more sparse the further back in time we look (see Chapter 4). This issue already suggests that more research should be conducted into the prevalence of early Upper Palaeolithic fire making (see Chapter 6). However, this project uses late Neandertals occupying Western Europe during the Last Glacial period (MIS 5–3) as the logical starting point to look for possible early evidence for fire making, given 1) Neandertals were regular users of fire; 2) the cold conditions endured by the Neandertals inhabiting the higher latitudes of Europe, especially during full-glacial conditions, provided a strong driving force to recognise and develop fire making technologies, and finally, 3) the prevalence of flint and pyrite-bearing carbonate bedrock in Western Europe made readily available (more or less) the requisite materials for making fire.

By gaining a better understanding of how Neandertals used fire, how these fire use practices might relate to the ability to produce fire at will, and how to identify fire making archaeologically, my research applies a multi-pronged approach to answering the question 'Did Neandertals make fire?'. This is reflected in the chapters comprising this dissertation, described in more detail in the sections below, wherein I present various goals and research questions being pursued. All four core chapters have been published in peer-reviewed journals. Chapter 2 confronts the archaeological evidence of fire use by Neandertals, in general, with a focus on the various factors that influence how we as archaeologists interpret fire signals within the Middle Palaeolithic record. Chapter 3 applies computer simulation in an attempt to model how some of the variables outlined in Chapter 2 can influence the relative production of fire proxy evidence under certain environmental conditions. Chapters 4 and 5 zoom in on the possibilities of using microwear analysis as a means for identifying direct evidence of fire making by Neandertals. Chapter 4 is primarily a theoretical and experimental exercise, wherein I describe the physical traces produced during experimental stone-on-stone fire making using flint and pyrite and the conditions whereby such traces are produced and their preservation potential are hypothesised. Chapter 5 applies these findings to a number of late Middle Palaeolithic assemblages of such curated items (bifaces) from France and presents probable microwear evidence for a novel Neandertal fire making method using these tools.

Chapter 2 – On the relationship between climate and Neandertal fire use during the Last Glacial in SW France

A group of researchers working at the French Middle Palaeolithic sites of Roc de Marsal and Pech de l'Azé IV (Dibble, et al., 2017; 2018b; Sandgathe, 2017; Sandgathe, et al., 2011a, 2011b) propose Neandertals were unable to produce fire for themselves and were thus reliant on natural sources of fire, presumably caused by lightning strikes, to provide opportunities to collect and curate this resource. They suggest reductions in lightning activity during colder climatic stadials during the Last Glacial period (MIS 5–3) led to a suppression of the natural fire regime in southwest France, thereby reducing Neandertal access to wildfires, which led to reduced evidence of fire use by these peoples (at least at the aforementioned sites) during these periods. They go on to suggest that, given this evidence, modern humans were the only hominins capable of making fire. Do the predictions of Sandgathe et al.'s 'very recent origin of fire production' hypothesis (2011a, 2011b) match the data on fire proxies and the environmental settings from Neandertal sites? What environmental, cultural and post-depositional taphonomic factors influence the production and preservation of combustion features (i.e.

hearths) and their associated fire residues (i.e. charcoal and ash) and fire proxy evidences (i.e. fire-affected lithic artefacts, faunal remains and underlying substrates)? And how would possessing the ability to make fire at will influence when and how fire is used, and how would this vary under different climatic conditions? This chapter provides a number of alternative explanations for observed variability in Neandertal fire use signals between cold and warm climatic periods.

Chapter 3 – fiReproxies: A computational model providing insight into heat-affected archaeological lithic assemblages

Fire size, duration and frequency (a function of the nature and availability of fuel sources) and site occupation dynamics are only a few of the factors discussed in Chapter 2 that can potentially influence the relative strength of anthropogenic fire signals. Site surface area, sedimentation rates, as well as the moisture content and thermal conductivity of the substrate underlying a hearth (among others) can also positively or negatively impact the number of fire proxies (specifically here, heated lithic artefacts) produced within an archaeological layer. Relatively speaking, how do these factors influence the number of heated lithics produced within an archaeological layer? In what ways do changes in site conditions affect these factors and their relative impact on fire signals? And what are the implications of these changes for how we interpret fire signals within or between archaeological sites based on fire proxy data? Chapter 3 attempts to provide quantitative answers to these questions through computer simulation using the 'fiReproxies' model designed for this research using the program R. The model allows users to tabulate the expected percentages of heated lithics produced over the course of multiple occupation episodes within an archaeological layer (of a given surface area) by adjusting the values set for the various parameters listed above per occupation of the site based on hypothetical environmental or cultural conditions. These tabulated percentages can then be compared to known heated lithic percentages from an archaeological site in an effort to understand which combinations of parameter values could have resulted in these values. Which combination of parameter values might be the most parsimonious explanation for the observed percentages can be determined through the comparison with known palaeoenvironmental proxy data (e.g. fauna or pollen assemblages) and other geological (e.g. estimated sedimentation rates) and/or archaeological evidences (e.g. other fire proxy data or evidence pertaining to group mobility or site function).

Chapter 4 – Fire production in the deep past: The expedient strike-a-light model

The (semi-)regular use of fire by Neandertals is attested to by the presence of combustion features and fire proxy evidence at numerous Middle Palaeolithic archaeological sites throughout Eurasia (Roebroeks and Villa, 2011a). However, the frequency with which fire was used, even if at times very high, says nothing about whether Neandertals were able to produce fire artificially or were just effective collectors and conservators of naturally occurring fire. Ultimately, as stated previously, the only way to determine if a group was capable of producing fire at will is to identify direct evidence of fire making, i.e. the fire making tools themselves. But how might fire making tools from (Middle) Palaeolithic contexts differ from those recovered from later Mesolithic, Neolithic and Bronze Age sites? How would this affect our ability to identify such tools? And is there evidence in the European Middle Palaeolithic record that indicates the utilization of a stone-on-stone method for producing fire? Using a microwear analytical approach and operating under what I call the 'expedient strike-a-light model', I hypothesise in Chapter 4 that within Middle Palaeolithic flake-based industries, the flint 'strike-a-light' elements of the stone-on-stone fire making tool kit were not formalised tools, but were instead selected on an ad hoc basis and were likely only used very briefly before being discarded, reducing their 'findability' in the archaeological record. Through experimentation and microwear analysis, I describe how the classic suite of strike-a-light use traces manifest, as well as how associated traces may appear on the pyrite ‘sparking’ element of the fire making kit, thereby providing archaeologists with a ‘guidebook’ for recognising possible Middle Palaeolithic fire making tools., These ideas were put to the test through the analysis of multiple northwest European Middle Palaeolithic lithic assemblages in an attempt to identify pieces with traces comparable to those observed on my experimental fire making tools, though these analyses ultimately yielded negative results.

Chapter 5 – Neandertal fire-making technology inferred from microwear analysis

Given that no apparent strike-a-lights were observed among these assemblages, it was decided to refocus my efforts on assemblages containing curated tools. As was also postulated within the expedient strike-a-light model, curated tools (like bifaces and large scrapers) should have a higher probability of preserving strike-a-light microwear traces simply due to their longer use lives (assuming that, at some point, they were used to make fire). Moreover, these traces, unless imparted onto the tool late in its use life, could be either obscured through subsequent use of the tool or removed entirely through resharpening, relegating the evidence for fire making to the debitage. Through the course of my earlier research, I learned that unidentified ‘mineral traces’ had been observed both on a number of late Middle Palaeolithic bifacial tools (often called ‘hand axes’) and associated bifacial thinning flakes (i.e. biface shaping and resharpening flakes) in lithic assemblages attributed to the Mousterian of Acheulian Tradition (or MTA) in France (Claud, 2008, 2012; Soressi, et al., 2008). How do these mineral traces compare with experimental traces produced during fire making? And how do both the archaeological traces and experimental pyrite traces compare with those produced by other rocks and minerals during various percussive or frictional activities? As with the previous study, answers to these questions were sought through practical experimentation with replica bifacial tools used in conjunction with different mineral materials and the microscopic analysis of the resulting use wear traces.

Chapter 6 – Conclusion

The final chapter of this dissertation provides a synthesis of the research described in Chapters 2–5, describing how the findings fit into the ongoing debate over when and where fire became an integral part of the hominin technological repertoire and outlining future avenues of research into this most interesting topic.

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