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

Sorensen, A.C.

Author: Sorensen, A.C.
Title: Beyond prometheus: pursuing the origins of fire production among early humans
Issue Date: 2018-12-13

6. Conclusion

The papers that comprise this dissertation apply different approaches to understanding if, how and when Neandertals made fire. Given the paucity of Middle Palaeolithic fire making technology known from the archaeological record, Chapters 2 and 3 discuss and assess the more traditional indirect arguments used by archaeologists to broach the subject, namely pointing to relative increases in the abundances of archaeological fire proxies at Middle Palaeolithic sites through time and the use of advanced pyrotechnologies to infer Neandertal fire production. Understanding better how fire-affected artefact 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. With this in mind, Chapters 4 and 5, take a more direct approach to identifying evidence of Middle Palaeolithic fire making by looking into the possible existence of fire production technology within Neandertal artefact assemblages.

In their original 2011 article, and reinforced in later papers (Dibble, et al., 2017, 2018; Sandgathe, 2017; Sandgathe, et al., 2011b), Sandgathe et al. offer a unique new take on the relationship between Neandertals 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 Neandertals were reliant on collecting fire from lightning-ignited conflagrations—presumed to be more prevalent during warm weather occupation phases—and were, thus, unable to make fire themselves. Chapter 2 pursues multiple lines of evidence to evaluate these claims and, ultimately, finds them lacking. It is demonstrated that lightning and fire regimes would not have been reduced to the point to preclude regular access to natural fires in the region by Neandertals, 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 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 Neandertals were certainly proficient at controlling fire, and possibly even making fire.

Chapter 2 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 Neandertal toolkit. Perhaps most importantly, reduced fuelwood availability (especially within the immediate vicinity of upland sites like Roc de Marsal and Pech de l’Azé IV) would have led to increased fuel economisation. Moreover, increased mobility brought on by a reliance on highly mobile reindeer, which comprise the majority of prey species observed at these sites during cold climatic intervals (presumably MIS 4 and early MIS 3), would have changed how and when Neandertals used the sites, thereby also affecting the frequency and intensity of fire use. The recurrent use of a camp or habitation site is often linked to subsistence strategies, these being related to the seasonal presence of plant or animal resources (Binford, 1978, 1980; Delagnes and Rendu, 2011; Rendu, et al., 2011). Within Middle Palaeolithic contexts, this would have likely concerned the distribution of dominate prey animal species being predated upon by Neandertal groups. Under conditions where a prey species were more or less evenly distributed throughout the environment, for example red deer in forested environments, groups likely occupied smaller home ranges. This would mean that a site within their home range may have been visited more frequently (maybe multiple times a year) and at any point in the year. In situations where the distribution of migratory prey species was highly seasonal, like for reindeer, which tend to follow an annual migration route characterised by aggregation periods during the spring and especially in the fall (cf. Burch, 1972), the occupation of certain sites would likely have been more seasonal and based on where the site was located within the reindeer migration route. However, which route reindeer will follow during the spring or fall migration is variable and often unpredictable (Binford, 1978; Burch, 1972), meaning that a site may not be occupied at all some years if alternative routes are 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 could be very limited, suggesting a potential reduction in the intensity and frequency with which some sites along this route are occupied.

Fuel economisation and mobility become further intertwined when one considers the fact that the location of fuel sources in the landscape would have factored greatly into decisions regarding the placement of short-term camps and, especially, longer term habitation sites, as is the case among modern hunter-gatherer groups located in fuel-sparse environments (Binford, 1978). Together, these two variables alone may have led to reduced fire signals simply through less frequent or intense use of these sites, in general, as well as the use of fewer, smaller, shorter burning fires, which tend to leave weaker archaeological signatures. Ultimately, I suggest 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.

The feasibility of the hypotheses outlined in Chapter 2 was tested in Chapter 3 through computer-based simulations using our 'fiReproxies' model. Our findings in this small proof-of-concept study lend credence to the assertions made in Chapter 2, primarily that under certain conditions—namely those that could be expected during colder climatic periods—estimated heated lithics 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 These results have major implications for how archaeologists 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. It is my intention to apply the model to real-world sites like Grotte Mandrin (mentioned above). Here, the variability in layered soot deposits in carbonate concretions linked to individual archaeological layers could provide a high temporal resolution against which more palimpsestic hearth and fire proxy frequencies could be compared (within and between layers) and used to test the accuracy of the model.

Gaining a better understanding of the variables potentially influencing Neandertal fire use practices has provided a basis on which I could more deeply explore how, if at all, fire making factored into their decisions regarding fire use, and perhaps more importantly, how one can recognise this practice archaeologically. In Chapter 4, I hypothesise that Neandertal fire making tools (i.e. flint strike-a-lights used in conjunction with fragments of pyrite to make sparks)—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 Neandertal stone tool technology (compared to the more formalised and curated tool kits of later Stone

Age peoples), I propose Middle Palaeolithic fire making tools were also, by and large, short-term, single use items.

Building on previous microwear research identifying percussive fire making tools (Beugnier and Pétrequin, 1997; Collin, et al., 1991; Guéret, 2013; Rots, 2012; Stapert and Johansen, 1999; van Gijn, et al., 2006), this chapter describes the classic suite of strike-a-light use traces observed on more recent, heavily used Neolithic and Bronze Age pieces (i.e. rounding and/or crushing of tool edges or surfaces containing zones of mineral polish and clustered, oriented striations) and then, through experimentation, determines how these traces translate onto tools that are only used for a brief period of time (i.e. one fire making event). As expected, the traces were 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.

Despite these negative results, the findings from this study have additional implications for how we interpret other aspects of the Palaeolithic archaeological record. For example, the use traces imparted onto the pyrite fragments while producing sparks are also described, usually appearing as artificially flattened or concave surfaces. Perhaps more important, however, were the 'abraded' surfaces incidentally created along the edges of broken pyrite nodule fragments on the iron oxide (goethite or hematite) 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.

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 Palaeolithic groups, making its presence at Palaeolithic 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, pers.comm.), giving an indication of the importance to this resource to Neandertals. 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 Palaeolithic 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 described in more detail in Chapter 4 (see also Larkin, 2011; Leduc, et al., 2012). Therefore, barring special depositional settings (e.g. rapid burial in a karstic setting), 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.

Moreover, 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 artefacts (personal observation, unpublished experiments). If this method was used during the Palaeolithic, it could provide yet another reason for the presence of so few 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 Palaeolithic archaeological sites as proof-positive indicators of fire making. Nevertheless, the recovery of pyrite at a Palaeolithic site could indicate a higher probability for the presence of strike-a-light tools within the lithic assemblage, thus helping to guide future research.

The final chapter comprising this dissertation (Chapter 5) explores an alternative facet of the expedient strike-a-light model described in Chapter 4 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. In fact, 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 observe 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 Palaeolithic. If this interpretation is correct, then this study provides the first definitive proof of regular fire making by pre-modern humans.

These findings are almost certainly not the final word on this subject. The possible strike-a-light identified at Bettencourt in northern France (Rots, 2011, 2015; Sorensen and Rots, 2014) pre-dates these MTA fire making tools by 25–35,000 years, potentially indicating an older origin of this practice. This finding demonstrates that, despite the inherent difficulties in identifying expedient strike-a-lights—as the failures to identify such tools in other Middle Palaeolithic collections described in Chapter 4 testify to—these tools are still recognisable in flake-based Mousterian industries and will likely be identified more often once analysts make a more concerted effort to seek them out.

6.1 Discerning 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. For this latter scenario, 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 but 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 localised 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 until these tools are identified, we are still largely reliant on proxy evidence for fire making (outlined in Chapter 1) to answer questions regarding the early origins of fire making.

6.1.1 Wood-on-wood friction verses stone-on-stone percussion

There is still uncertainty as to whether wood-friction or stone-on-stone percussion was the first fire making system (Watson, 1939; Weiner, 2003). Some researchers even debate themselves on this matter (Hough, 1926, 1928). Many researchers tend to believe that the analogous nature of the stone-on-stone method to flintknapping suggest this was likely the earliest method for fire production (Oakley, 1961; Watson, 1939; Weiner, 2003). Conversely, the simple act of rubbing one’s hands on the body or clothes to warm up helps to make the connection between friction and heat. This could then be extrapolated to friction between other materials, with the close association between wood and fire potentially evoking the idea that fire was contained within the wood. 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 (Ambrose, 1998; Collina-Girard, 1993; McBrearty and Brooks, 2000; Orton, 2008; Thompson, et al., 2004; Werner and Willoughby, 2018) and/or during the UP in Eurasia (Martí, et al., 2017; Wei, et al., 2017)—in parallel with analogous evidence of drilling technology (Hough, 1926, 1928; Kidder, 1994; Oakley, 1961). Pointing to the ethnographic record, others go on to argue that the more localised 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. 1), 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 carbonised wood from Kalambo Falls in Zambia exhibiting curious grooves could represent an early example of the fire-plough (Leroi-Gourhan, 1994; Oakley, 1961). 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 (Allington-Jones, 2015; Aranguren, et al., 2018; Carbonell and Castro-Curel, 1992; Movius Jr, 1950; Rios-Garaizar, et al., 2018; Thieme, 1997;

Thieme and Veil, 1985), 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 artefacts having been interpreted as fire making equipment coming from Middle and Upper Palaeolithic deposits (see Collina-Girard, 1993, 1998), like the purported Krapina fire drill (Gorjanovic-Kramberger, 1919), 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 Collina-Girard, 1993, 1998; Roussel, 2005, and sources therein).

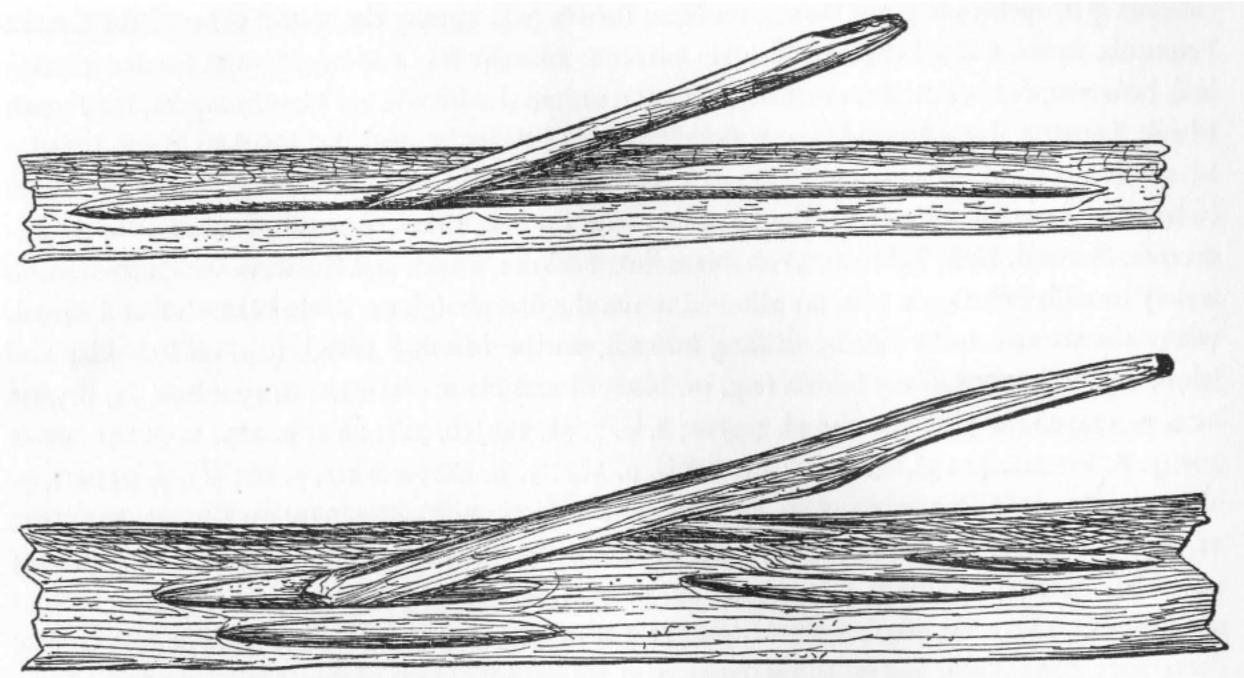

Figure 1. Ethnographic fire-ploughs from Tuamotu Islands (upper) and Jaluit (lower) (after Lagercrantz, 1954).

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 after the influx of European colonists to the continent (see Roussel, 2005, and notes; Lagercrantz, 1954). This could be partially due to the paucity of pyrite-bearing rock formations in Africa, or if present, poor preservation (both at the time and archaeologically) due to the warmer climate. 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 East Stone Age sites, nor in the Levant despite the presence of pyrite nodule-bearing outcrops located in southern Israel (Sass, et al., 1965). Nevertheless, regular fire use appears to have been a relatively early phenomenon in the Levant (e.g. Alperson-Afil, 2008; Friesem, et al., 2014; Karkanas, et al., 2007; Meignen, et al., 2008; 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 in Chapters 2 and 3? While it is yet difficult to say for sure, what is certain is that, to date, no strike-a-lights, nor pyrite fragments, have been recovered from Tabun (Shimelmitz, pers. comm.).

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 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 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 then carried out of Africa into Eurasia. The paucity of evidence for rotational drilling technology in Eurasian Middle Palaeolithic assemblages could indicate that Neandertals at least did not employ the fire-drilling technique, but the fire-plough method may have been employed, though evidence for this method is also lacking. Conversely, the stone percussion fire making method was possibly a European (or Eurasian) innovation, perhaps initially introduced by (early?) Neandertals (Monnier and Hallegouet, 2004; Rots, 2015; Sorensen and Rots, 2014; 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 Neandertals (cf. Soressi, et al., 2013). This could potentially explain the paucity of percussive fire making tools in the early Upper Palaeolithic.

6.2 Future Directions

6.2.1 Identifying pyrite residues on Palaeolithic tools

While the microwear evidence of fire production by Neandertals presented in Chapter 5 is strong, these interpretations could be 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 Palaeolithic 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 tools interpreted as strike-a-lights (Lombardo, et al., 2016; Pawlik, 2004). However, since no pyritic residues were observed on the MTA bifaces analysed in Chapter 5, the usefulness of these particular methods as prospection tools for detecting optically-invisible pyritic micro-residues should be explored further.

6.2.2 Looking backwards: Fire making in the Quina Mousterian?

The difficulties associated with identifying strike-a-lights among the thousands of lithic artefacts generated within flake-based industries remain problematic due to the sheer number of artefacts contained within these assemblages. Given the variability in gestures one could employ to make fire using the stone-on-stone method, any one of these artefacts 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. However, the identification of probable strike-a-light microwear traces on numerous Middle Palaeolithic bifaces, as described in Chapter 5, provides perhaps a more promising point of departure than the systematic analysis of whole lithic assemblages described above and in Chapter 3. Curated chipped-stone tools found within some stone tool industries—these often defining the industry itself, as in the case of MTA bifaces—provide focal points on which special attention should be paid for seeking out potential evidence for use as fire makers. The longer use-lives of these tools (Geneste, 1985; Soressi, 2002, 2004), coupled with their tendency to be well-travelled and used for multiple tasks (Claud, 2008; Soressi and Hays, 2003), 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 Chapters 4 and 5 to older lithic industries with curated tools like the Quina Mousterian and the Acheulean could potentially push back the earliest evidence for fire making by hominin groups deeper into the Palaeolithic. And indeed, the use of flattish, flaked interior 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 places fire making well within the realm of possible uses for these tools.

6.2.3 Looking forwards: Fire use and fire making in the early Upper Palaeolithic

While the potential for extending our knowledge of fire making further back into Palaeolithic is an exciting prospect, it should be remembered that evidence for fire production by early Upper Palaeolithic modern humans is also very scant. To my knowledge, no Aurignacian strike-a-lights have been identified to date using microwear analysis, though there are a number of tools described in the literature that are potentially good candidates (Bardon, et al., 1908; Bouyssonie, et al., 1913; Patte, 1937; Symens, 1988). There is one Gravettian or Protoaurignacian strike-a-light inferred from microwear analysis (Slimak and Plisson, 2008), but most Upper Palaeolithic examples come from post-Last Glacial Maximum contexts (i.e. from the Magdalenian onward; see Table 1 in Chapter 4). Upper Palaeolithic pyrite specimens are equally elusive (see Table 2 in Chapter 4). Despite this paucity of Upper Palaeolithic fire making tools, there does not appear to be any real controversy surrounding the abilities of the earliest modern humans in Eurasia to make fire. Moreover, it has been suggested that more frequent use of fire by Upper Palaeolithic peoples implies they likely made fire at will (Sandgathe, et al., 2011a, 2011b), though it has been pointed out that Upper Palaeolithic record of fire use is far from continuous (Roebroeks and Villa, 2011b). If the standards applied by Sandgathe et al. are thus applied to the Upper Palaeolithic, then some of these peoples also lacked the ability to make fire. Or more likely, as argued in Chapter 2, it could be that these people also regularly used fire, but both its use and the preservation of fire traces are highly variable. And assuming modern humans in Eurasia were always able to make fire at will, then there must be a similar problem of identifying the tools used to make fire during the Upper Palaeolithic as there is for the Middle Palaeolithic. Therefore, more research should be conducted into 1) clarifying the Upper Palaeolithic fire use record, in line with what Roebroeks and Villa (2011a) did for the Middle Palaeolithic fire record, and 2) giving more attention to identifying possible fire making equipment from this period.

6.3 Final Thoughts

The ideas for future research trajectories described above demonstrate that questions still remain regarding fire use and the possibilities for fire making among Palaeolithic peoples. Indeed, the subject will likely remain contentious, as recent publications show that other researchers are not in agreement with some of the findings and assertions contained within this dissertation (see Dibble, et al., 2017, 2018). The purpose of this project was not 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 Neandertals, and to provide food for thought for continued discussion on this heated topic. If scientific knowledge is fuelled by burning questions like those confronted here, it is healthy disagreement that helps to fan the flames, allowing our collective knowledge to grow and spread.

References

Allington-Jones, L., 2015. The Clacton Spear: The Last One Hundred Years, *Archaeological Journal* 172, 273-296.

Alperson-Afil, N., 2008. Continual fire-making by Hominins at Gesher Benot Ya'aqov, Israel, *Quaternary Science Reviews* 27, 1733-1739.

Ambrose, S.H., 1998. Chronology of the Later Stone Age food production in East Africa, *Journal of Archaeological Science* 25, 377-392.

Aranguren, B., Revedin, A., Amico, N., Cavulli, F., Giachi, G., Grimaldi, S., Macchioni, N., Santaniello, F., 2018. Wooden tools and fire technology in the early Neanderthal site of Poggetti Vecchi (Italy), *Proceedings of the National Academy of Sciences*, 201716068.

Bardon, L., Bouyssonie, A., Bouyssonie, J., 1908. Station préhistorique de la Coumba-del-Bouïtou, près Brive (Corrèze), *Bulletin de la Société Scientifique, Historique et Archéologique de la Corrèze* 30.

Beugnier, V., Pétrequin, P., 1997. Pierres à briquet: utilisation de la marcassite, in: Pétrequin, P. (Ed.), *Les sites littoraux néolithiques de Clairvaux-les-Lacs et de Chalain (Jura), III. Chalain station 3, 3200–2900 av. J.-C. (Volume III)*, Maison des Sciences de l'Homme, Paris, pp. 429-434.

Beyries, S., Walter, P., 1996. Racloirs et colorants à Combe-Grenal. Le problème de la retouche Quina, *Quaternaria Nova* 6, 167-187.

Binford, L.R., 1978. *Nunamiut Ethnoarchaeology*, Academic Press, New York.

Binford, L.R., 1980. Willow Smoke and Dogs' Tails: Hunter-Gatherer Settlement Systems and Archaeological Site Formation, *American Antiquity* 45, 4-20.

Bonjean, D., Di Modica, K., Abrams, G., Pirson, S., Otte, M., 2011. La grotte Scladina: bilan 1971-2011, in: Toussaint, M., Di Modica, K., Pirson, S. (Eds.), *Le Paléolithique moyen en Belgique. Mélanges Marguerite Ulrix-Closset*, Service de Préhistoire de l'Université de Liège, Liège, pp. 323-334.

Bouyssonie, J., Bouyssonie, A., Bardon, L., 1913. La station préhistorique de Font-Yves (Corrèze), *Revue anthropologique* 23, 218-225.

Burch, E.S., Jr., 1972. The Caribou/Wild Reindeer as a Human Resource, *American Antiquity* 37, 339-368.

Carbonell, E., Castro-Curel, Z., 1992. Palaeolithic wooden artefacts from the Abric Romani (Capellades, Barcelona, Spain), *Journal of Archaeological Science* 19, 707-719.

Claud, É., 2008. Le statut fonctionnel des bifaces au Paléolithique moyen récent dans le Sud-Ouest de la France: Étude tracéologique intégrée des outillages des sites de La Graulet, La Conne de Bergerac, Combe Brune 2, Fonseigner et Chez-Pinaud / Jonzac, Université Bordeaux I, p. 546.

Claud, É., 2012. Les bifaces: des outils polyfonctionnels? Étude tracéologique intégrée de bifaces du Paléolithique moyen récent du Sud-Ouest de la France, *Bulletin de la Société préhistorique française* 109, 413-439.

Collin, F., Mattart, D., Pirnay, L., Speckens, J., 1991. L'obtention du feu par percussion: approche expérimentale et tracéologique, *Bulletin des chercheurs de la Wallonie* 31, 19-49.

Collina-Girard, J., 1993. Feu par percussion, feu par friction, *Bulletin de la Société préhistorique française* 90, 159-176.

Collina-Girard, J., 1998. *Le Feu avant les allumettes: expérimentation et mythes techniques*, Maison des Sciences de l'Homme (CID), Paris.

Delagnes, A., Rendu, W., 2011. Shifts in Neandertal mobility, technology and subsistence strategies in western France, *Journal of Archaeological Science* 38, 1771-1783.

Dibble, H.L., Abdolahzadeh, A., Aldeias, V., Goldberg, P., McPherron, S.P., Sandgathe, D.M., 2017. How did hominins adapt to ice age Europe without fire?, *Current Anthropology* 58, S278-S287.

Dibble, H.L., Sandgathe, D., Goldberg, P., McPherron, S., Aldeias, V., 2018. Were Western European Neandertals Able to Make Fire?, *Journal of Paleolithic Archaeology* 1, 54-79.

Friesem, D.E., Zaidner, Y., Shahack-Gross, R., 2014. Formation processes and combustion features at the lower layers of the Middle Palaeolithic open-air site of Nesher Ramla, Israel, *Quaternary International* 331, 128-138.

Geneste, J.-M., 1985. Analyse lithique d'industries moustériennes du Périgord: une approche technologique du comportement des groupes humaines au Paléolithique moyen, University of Bordeaux, Bordeaux, p. 567.

Gorjanovic-Kramberger, K., 1919. Uber ein vermutliches Feuerholz des Homo primigenius aus Krapina', *Verh. Ges. Deutsch. Natur. u. Arzte* 81, 211-213.

Guéret, C., 2013. L'outillage du Premier Mésolithique dans le Nord de la France et en Belgique. Eclairages fonctionnels, Université Panthéon-Sorbonne, Paris, p. 472.

Hayden, B., 1993. The cultural capacities of Neandertals: a review and re-evaluation, *Journal of Human Evolution* 24, 113-146.

Hough, W., 1926. *Fire as an agent in human culture*, Government Printing Office, Washington D.C.

Hough, W., 1928. Fire-making Apparatus in the United States National Museum, *Proceedings of the United States National Museum* 73.

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

Kidder, N., 1994. Fire, *Bulletin of Primitive Technology* 8, 77-78.

Lagercrantz, S., 1954. *African methods of fire-making*, Almqvist & Wiksells Boktryckeri, Uppsala.

Larkin, N.R., 2011. Pyrite Decay: cause and effect, prevention and cure, *NatSCA News* 21, 35-43.

Leduc, T., Goemaere, É., Jadin, I., Cattelain, P., 2012. L'altération des briquets en «marcassite» du «Trou de Chaleux» (fouilles d'Édouard Dupont) : identification des phases minérales primaires et secondaires, *ArcheoSciences* 36, 85-93.

Leroi-Gourhan, A., 1994. *Dictionnaire de la Préhistoire*, Presses Universitaires de France (PUF), Paris.

Lombardo, T., Grolimund, D., Kienholz, A., Hubert, V., Wörle, M., 2016. The use of flint-stone fragments as “fire-strikers” during the Neolithic period: Complementary micro-analytical evidences, *Microchemical Journal* 125, 254-259.

Martí, A.P., Wei, Y., Gao, X., Chen, F., d'Errico, F., 2017. The earliest evidence of coloured ornaments in China: The ochred ostrich eggshell beads from Shuidonggou Locality 2, *Journal of Anthropological Archaeology* 48, 102-113.

McBrearty, S., Brooks, A.S., 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior, *Journal of Human Evolution* 39, 453-563.

Meignen, L., Goldberg, P., Albert, R.M., Bar-Yosef, O., 2008. Structures de combustion, choix des combustibles et degré de mobilité des groupes dans le paléolithique moyen du Proche-Orient (grottes de Kébara et d'Hayonim, Israël), in: Théry-Parisot, I., Costamagno, S., Henry, A. (Eds.), *Gestion des combustibles au paléolithique et au mésolithique : nouveaux outils, nouvelles interprétations, UISPP XV congress, BAR International Series 114*, Archaeopress, Oxford, pp. 101-118.

Monnier, J., Hallegouet, B., 2004. Rapport intermédiaire sur la fouille du gisement paléolithique inférieur de Menez-Dregan I, campagne 2004, UMR 6566 du CNRS, Rennes.

Movius Jr, H.L., 1950. A wooden spear of third interglacial age from lower Saxony, *Southwestern Journal of Anthropology* 6, 139-142.

Oakley, K.P., 1961. On man's use of fire, with comments on tool-making and hunting, in: Washburn, S.L. (Ed.), *Social Life of Early Man*, Aldine Publishing Co., Chicago, pp. 176-193.

Orton, J., 2008. Later Stone Age ostrich eggshell bead manufacture in the Northern Cape, South Africa, *Journal of Archaeological Science* 35, 1765-1775.

Overlaet, B., 2008. Great balls of fire? Pyrites, meteorites and meteor-wrongs from ancient Iran, *Iranica Antiqua* 43, 153-165.

Patte, E., 1937. Sur une particularité de certaines lames aurignaciennes à étranglement, *Bulletin de la Société préhistorique de France* 34, 447-449.

Pawlik, A., 2004. An Early Bronze Age pocket lighter, in: Walker, E.A., Wenban-Smith, F., Healy, F. (Eds.), *Lithics in Action: Papers from the conference Lithic Studies in the Year 2000*, Oxbow Books, Oxford, pp. 149-151.

Rendu, W., Bourguignon, L., Costamagno, S., Meignen, L., Soulier, M.-C., Armand, D., Beauval, C., David, F., Griggo, C., Jaubert, J., 2011. Mousterian hunting camps: interdisciplinary approach and methodological considerations, *Palethnologie* 3, 59-73.

Rios-Garaizar, J., López-Bultó, O., Iriarte, E., Pérez-Garrido, C., Piqué, R., Aranburu, A., Iriarte-Chiapusso, M.J., Ortega-Cordellat, I., Bourguignon, L., Garate, D., 2018. A Middle Palaeolithic wooden digging stick from Aranbaltza III, Spain, *PLoS ONE* 13, e0195044.

Roebroeks, W., Villa, P., 2011a. On the earliest evidence for habitual use of fire in Europe, *Proceedings of the National Academy of Sciences* 108, 5209-5214.

Roebroeks, W., Villa, P., 2011b. Reply to Sandgathe et al.: Neandertal use of fire, *Proceedings of the National Academy of Sciences* 108, E299.

Rots, V., 2011. Tool use and hafting in the western European Middle Palaeolithic, in: Toussaint, G., Di Modica, K., Pirson, S. (Eds.), *Le Paléolithique Moyen en Belgique. Mélanges Marguerite Ulrix-Closset*, ERAUL 128, University of Liège, Liège, pp. 277-287.

Rots, V., 2012. Trace formation, strike-a-lights, and the contribution of functional analyses for understanding Palaeolithic contexts, in: Niekus, J.L.T., Barton, R.N.E., Street , M., Terberger, T. (Eds.), *A Mind set on Flint. Studies in Honour of Dick Stapert*, Barkhuis, Groningen, pp. 149-162.

Rots, V., 2015. Hafting and the interpretation of site function in the European Middle Palaeolithic, in: Conard, J., Delagnes, A. (Eds.), *Settlement Dynamics of the Middle Paleolithic and Middle Stone Age*, Kerns Verlag, Tübingen, pp. 383-410.

Roussel, B., 2005. *La production du feu par percussion de la pierre: Préhistoire, ethnographie, expérimentation*, Editions Monique Mergoil, Montagnac.

Sandgathe, D.M., 2017. Identifying and describing pattern and process in the evolution of hominin use of fire, *Current Anthropology* 58, S360-S370.

Sandgathe, D.M., Dibble, H.L., Goldberg, P., McPherron, S.P., Turq, A., Niven, L., Hodgkins, J., 2011a. On the Role of Fire in Neandertal Adaptations in Western Europe: Evidence from Pech de l'Azé and Roc de Marsal, France., *PaleoAnthropology*, 216-242.

Sandgathe, D.M., Dibble, H.L., Goldberg, P., McPherron, S.P., Turq, A., Niven, L., Hodgkins, J., 2011b. Timing of the appearance of habitual fire use, *Proceedings of the National Academy of Sciences* 108, E298.

Sass, E., Nathan, Y., Nissenbaum, A., 1965. Mineralogy of certain pyrite concretions from Israel and their alteration products, *Mineralogical Magazine* 35, 84-87.

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

Shimelmitz, R., Kuhn, S.L., Jelinek, A.J., Ronen, A., Clark, A.E., Weinstein-Evron, M., 2014. 'Fire at will': The emergence of habitual fire use 350,000 years ago, *Journal of Human Evolution* 77, 196-203.

Slimak, L., Plisson, H., 2008. La sépulture paléolithique de l'enfant du Figuier (Ardèche, France). Emboîtement d'une symbolique funéraire, in: Bailly, M., Plisson, H. (Eds.), *La valeur fonctionnelle des objets sépulcraux, Actes de la table ronde d'Aixen-Provence, 25–27 octobre 2006*, Préhistoire Anthropologie Méditerranéennes 14, pp. 29-38.

Sorensen, A., Rots, V., 2014. Testing the 'expedient strike-a-light model': An experimental assessment based on the first identified Middle Palaeolithic fire-maker from Bettencourt (France), *Union Internationale des Sciences Préhistoriques et Protohistoriques (UISPP) XVII*, Burgos, Spain, pp. 1005-1006.

Sorensen, A.C., Claud, E., Soressi, M., 2018. Neandertal fire-making technology inferred from microwear analysis, *Scientific Reports* 8, 10065.

Soressi, M., 2002. Le Moustérien de tradition acheuléenne du sud-ouest de la France. Discussion sur la signification du faciès à partir de l'étude comparée de quatre sites: Pech-de-l'Azé I, Le Moustier, La Rochette et la Grotte XVI, University of Bordeaux I, Bordeaux, p. 330.

Soressi, M., 2004. From Mousterian of acheulian tradition type A to type B: technical tradition, raw material, task, or settlement dynamic changes? , in: Conard, N.J. (Ed.), *Settlement dynamics of the Middle Paleolithic and Middle Stone Age, volume 2*, Tübingen Publications in Prehistory, Tübingen, pp. 343-366.

Soressi, M., Hays, M.A., 2003. Manufacture, transport and use of Mousterian bifaces. A case study from the Perigord (France), in: Soressi, M., Dibble, H. (Eds.), *Multiple approaches to the study of bifacial technologies*, The University of Pennsylvania Museum Press, Philadelphia, pp. 125-147.

Soressi, M., McPherron, S.P., Lenoir, M., Dogandžić, T., Goldberg, P., Jacobs, Z., Maigrot, Y., Martisius, N.L., Miller, C.E., Rendu, W., Richards, M., Skinner, M.M., Steele, T.E., Talamo, S., Texier, J.-P., 2013. Neandertals made the first specialized bone tools in Europe, *Proceedings of the National Academy of Sciences* 110, 14186-14190

Soressi, M., Rendu, W., Texier, J.-P., Claud, E., Daulny, L., D'errico, F., Laroulandie, V., Maureille, B., Niclot, M., Schwortz, S., Tillier, A.-M., 2008. Pech-de-l'Azé I (Dordogne, France): nouveau regard sur un gisement moustérien de tradition acheuléenne connu depuis le XIX siècle, in: Jaubert, J., Bordes, J.-G., Ortega, I. (Eds.), *Les sociétés Paléolithiques d'un grand Sud-Ouest: nouveaux gisements, nouvelles méthodes, nouveaux résultats*, Société Préhistorique française, Paris, pp. 95-132.

Stapert, D., Johansen, L., 1999. Flint and pyrite: making fire in the Stone Age, *Antiquity* 73, 765-777.

Symens, N., 1988. Gebrauchsspuren der Steinartefakte, in: Hahn, J. (Ed.), *Geißenklösterle 1. Forschungen und Berichte zur Vor-und Frühgeschichte in Baden-Württemberg 26*, Kondrad Theiss Verlag, Stuttgart, pp. 177-201.

Thieme, H., 1997. Lower Palaeolithic hunting spears from Germany, *Nature* 385, 807-810.

Thieme, H., Veil, S., 1985. Neue Untersuchungen zum eemzeitlichen Elefanten-Jagdplatz Lehringen, Ldkr. Verden, *Die Kunde* 36, 11-58.

Thompson, J., Bower, J., Fisher, E., Mabulla, A., Marean, C., Stewart, K., Vondra, C., 2004. Loiyangalani: behavioral and taphonomic aspects of a Middle Stone Age site in the Serengeti Plain, Tanzania, *PaleoAnthropology* 2004, A56.

van Gijn, A.L., van Betuuw, V., Verbaas, A., Wentink, K., 2006. Flint, procurement and use, in: Louwe Kooijmans, L.P., Jongste, P.F.B. (Eds.), *Schipluiden: a Neolithic settlement on the Dutch North Sea coast, c. 3500 cal BC*, Annalecta Praehistorica Leidensia, Leiden, pp. 129-165.

Vandevelde, S., Brochier, J., Desachy, B., Petit, C., Slimak, L., 2018. Sooted concretions: A new micro-chronological tool for high temporal resolution archaeology, *Quaternary International* 474, 103-118.

Vandevelde, S., Brochier, J.É., Petit, C., Slimak, L., 2017. Establishment of occupation chronicles in Grotte Mandrin using sooted concretions: Rethinking the Middle to Upper Paleolithic transition, *Journal of Human Evolution* 112, 70-78.

Watson, W.N., 1939. Methods of fire making used by early man, *Journal of Chemical Education* 16, 36-45.

Wei, Y., d'Errico, F., Vanhaeren, M., Peng, F., Chen, F., Gao, X., 2017. A technological and morphological study of Late Paleolithic ostrich eggshell beads from Shuidonggou, North China, *Journal of Archaeological Science* 85, 83-104.

Weiner, J., 2003. Friction vs. percussion. Some comments on firemaking from Old Europe, *Bulletin of Primitive Technology* 26, 10-16.

Weiner, J., Floss, H., 2004. Eine Schwefelkiesknolle aus dem Aurignacien vom Vogelherd, Baden-Württemberg - Zu den Anfängen der Feuererzeugung im europäischen Paläolithikum, *Archäologische Informationen* 27, 59-78.

Werner, J.J., Willoughby, P.R., 2018. Middle stone age point technology: Blind-testing the damage distribution method, *Journal of Archaeological Science: Reports* 19, 138-147.