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Burning flint: An experimental approach to study the effect of fire on flint tools

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ABSTRACT

Burnt lithic artefacts are regularly discarded from microwear analyses, causing a bias in the functional interpretation of prehistoric sites. This is especially true when burnt lithics are numerous as is typically the case on Mesolithic sites in Northern Belgium. Burnt stone artefacts potentially hold information regarding the functional, spatial, and social organisation of the site. Therefore, investigating the impact of burning on lithic tools, and especially on the preservation of microwear traces is crucial. In this paper, we present the experimental approach developed to tackle this problem. Flint tool replicas were burnt in several open fire experiments, organised to reproduce conditions that were realistic to those of the original prehistoric contexts. This way, we could evaluate the impact of different fuel types on the longevity and intensity of the fire. These experiments provide essential information on the effects of heat on the physical aspects of flint artefacts. Therefore, the relation between raw material characteristics and the degree of burning is studied as well. In addition, the results of the open fire experiments could be related to the spatial distribution of burnt flints in surface hearths. The findings are interpreted on a socio-economical level in order to better understand how and why lithics could have ended up in fire.

1. Introduction

Fire has been part of human life since at least hundreds of thousands of years (Chazan, 2017; Sorensen et al., 2018) and open fires and hearths were a highly important part of prehistoric sites from at least the Middle Palaeolithic (Aldeias, 2017). Therefore, fire has affected a non-negligible amount of the prehistoric material culture. The main part of preserved material culture from prehistoric Europe is made of stone, mostly flint (Renfrew and Bahn, 2004). During its life cycle, a flint tool could have been subjected to heating at different moments, for example during the initial fragmentation of raw material nodules (Guilbert, 2001), via heat treatment before knapping or by burning after it was discarded. Heat treatment is well-researched and many aspects of this process have been studied (Olausson, 1983; Domański and Webb, 1992, 2007; Schmidt et al., 2012, 2016, 2017). In the meantime, research on the impact of burning on flint tools after use and abandonment is insufficient and only a few studies focus on this problem (i.e. Clemente-Conte, 1997; Rutkoski et al., 2019; Sergant et al., 2006; Lawrence and Mudd, 2015; Gurova et al., 2020). Yet, burnt lithic material is present in archaeological collections, in many cases in very high quantities, e.g. at Early Mesolithic sites in Belgium the number of burnt lithics reaches up to 70% of the assemblages (Crombé et al., 2013). It is clear that a good understanding of the impact of heat on lithic artefacts offers interesting perspectives for reconstructing former (latent) hearths (Sergant et al., 2006), fire and occupation dynamics (Crombé et al., 2013; Lawrence and Mudd, 2015), as well as tool function. As the latter has so far hardly been studied, a major, multidisciplinary project aiming to investigate the impact of burning on the preservation of lithic microwear traces was initiated in 2016. These microscopic traces are developed on the surface of the artefacts by getting in contact with other materials. They appear as edge damages, polishes, scars and scratches, i.e. microdamages (Semenov and Thompson, 1964; Keeley, 1980). However, to understand the impact of fire on these traces, we have to be familiar with the characteristics of the flint and the fire themselves. In this study, we

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present a methodology applied to burn flint in an open fire setting. This prospective study was designed to investigate the impact of the longevity of firing, the maximum and mean temperature of burning, the alteration features present on the raw materials at different burning degrees, the effect of raw material characteristics on the presence of these features, and the position of the samples in the fire. The impact of these variables on the preservation of microwear traces will not be discussed in this paper, since this part of the project is still ongoing.

2. Materials and methods

2.1. *Archaeological context*

In our project, archaeological sites from North-Western Belgium are used as the basis for comparison and archaeological interpretation of the experimental results. Sites in Doel-Deurganckdok and Bazel-Sluis are dated to the transitional period of the Mesolithic-Neolithic (Crombé, 2005; Crombé et al., 2015; Meylemans et al., 2018). Verrebroek-Aven Ackers is a Late Mesolithic site (Robinson et al., 2011), while the main occupation of Kerkhove-Stuw belongs to the Early Mesolithic and several smaller concentrations of finds dates to the Middle Mesolithic (Vandendriessche et al., 2019) (Fig. 1). On all these Mesolithic sites, the mean number of burnt lithic artefacts, mainly made of flint, is high: Kerkhove, 10%; Verrebroek-Aven Ackers, 28%; Doel-Deurganckdok, 28% and Bazel-Sluis, 20%. On some other Mesolithic sites in the Lower Scheldt basin, e.g. Verrebroek-Dok 1 (Crombé et al., 2013), the proportion of burnt lithic artefacts even reaches 83%, compared to Palaeolithic or Neolithic sites.

2.2. *Open fire experiments*

2.2.1. *Methods*

We lit 7 fires in total, which will be discussed in detail below. Before the burning of the lithic samples, we tested different fire settings without stone artefacts (fire 1–4) to find the most fitting one for the experiments that also closely resembles prehistoric conditions. Based on the obtained results from these four trials, three additional experiments were conducted involving lithic samples (fire 5–7). The settings of each fire were based on archaeological data (i.e. fuel, base sediment, size of hearths) from mainly Belgian Mesolithic sites. For the selection of firewood, palaeobotanical information (palynological and anthracological data) from the studied sites was used (Deforce, 2014; Deforce et al., 2014; Crombé et al., 2019). During the Early Mesolithic, pine was the most present tree type; while during the Late Mesolithic, oak predominated the dry forests. Therefore, pine and oak were selected as primary fuel for all the experiments. All wood was dried for two to three years, the wood pieces were on average 20 cm by 25 cm; however, we chopped some smaller sticks as well to use as kindling. In the first three experiments, the firewood consisted of pine (fire 1), oak (fire 2), and a combination of pine and oak (fire 3) (Table 1).

As these two wood types have never been compared to each other, nor mixed in previous hearth experiments, it was important to study

Fig. 1. Map of research area with indication of the archaeological sites (red dots), the Cretaceous deposits (green area) in which flint was retrieved (green dots) for the experimental fires (adapted after Fiers et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
List of experimental campfires: fires 1 to 4 represent the fires without lithics, fires 5 to 7 include lithic material.

No.	Date	Size	Fuel type	Recorded max T (°C)	Fire duration	Experimental tools	Geological flakes
1	2018/08/30	∅ 56 cm	Pine wood	1100 °C	93 min	None	None
2	2018/08/30	∅ 56 cm	Oak wood	1100 °C	90 min	None	None
3	2018/08/30	∅ 56 cm	Oak and pine wood	1100 °C	90 min	None	None
4	2018/08/30	∅ 56 cm	Oak, pine and bone	1000 °C	140 min	None	None
5	2018/08/31	∅ 55 cm	Oak, pine and bone	1000 °C	240 min	None	138
6	2019/04/13	∅ 60 cm	Pine wood	850 °C	140 min	20	20
7	2019/04/13	∅ 60 cm	Oak wood	1000 °C	140 min	20	20

their burning properties before using them to burn lithics. The addition of bone was also considered for two reasons. First, at the studied prehistoric sites considerable amounts of burnt bones were recovered from latent surface hearths (Van Neer et al., 2013; Vandendriessche et al., 2019). In fact, accumulation of burnt bones is one of the proxies, besides charred plant remains such as carbonized hazelnut shells, used to identify surface hearths (Sergant et al., 2006). Secondly, the use of bone as fuel in fire is already known from the Middle Palaeolithic onwards (e.g. Morin, 2010; Yravedra and Uzquiano, 2013; Gabucio and Cáceres, 2014). Experimental studies have demonstrated that adding bones extends the duration of the burning process (Théry-Parisot, 2002; Aldeias, 2017). Therefore, we also experimented with adding animal bones (long bones from a red deer and cow) to the fire that was built from the combination of pine and oak (fire 4) (Table 1). The selection of bones was made based on practicality, i.e. what we had access to. Moreover, red deer was also an important game during the Mesolithic, as remains have been found at several of the involved sites (Van Neer et al., 2013; Vandendriessche et al., 2019).

The soil on which the experimental fires were built also resembled the soil conditions of the Mesolithic sites, which were all found on sandy inland dunes and levees. As the location of the experiments had a clay-rich humic soil, a 1 m by 1 m by 1 m hole was dug and filled up with river sand (Fig. 2). In doing so, we also normalised the ground base. The size of the hearths was set to approximately 1 m^2, which was based on the dimensions of the majority of known structured Mesolithic hearths in NW Europe (Sergant et al., 2006).

The fires were continuously monitored by recording proxies such as duration of burning, intensity, spread, and temperature changes. The middle of the fire and the underlying sediment was regularly measured with a Testo 835-T2 infrared thermometer (Fig. 2c). A FLIR A655sc heat camera recorded the temperature at 20 s resolution for the whole duration of burning (Fig. 2d). The heat camera allows different temperature range settings: −40 °C to 150 °C, 100 °C to 650 °C and 300 °C to 2000 °C. For the first five fires, the temperature range was switched between the setting 100–650 °C and 300–2000 °C, depending on the maximum temperature of the flames, because we wanted to monitor the fire temperature. For fire 6 and 7, the range was set to 100–650 °C for the whole duration, in order to monitor the temperature of the flint concentrations that were visible for the heat camera.

The data gained by the heat camera were processed with FLIR ResearchIR Max 4 software. For the second set of experiments (fire 6 and 7), a weather station was set up to have reliable data on the weather conditions. For the first set of experiments (fire 1 to 5), this equipment was not available, therefore, the weather conditions, such as wind

Fig. 2. Setting of fires without stone samples (fire 1–4) with equipment used for documentation. a) 1x1m square filled with river sand with fire made of pine wood. b) Measuring during fire with a Testo 835-T2 infrared thermometer. c) Top view of fire during smouldering. d) Setup of the FLIR A655sc heat camera and a DSLR camera.

strength and temperature are not precise enough and will not be presented here. In general, fire 1–5 were lit in August 2018 with temperatures around 30 °C and minimal air movement. The experiment with fire 6 and 7 was carried out in April 2019 and details of the weather are presented at the description of the experiments.

2.2.2. Fire 1

The first fire was built from pine wood and was 56 cm in diameter at the start and was lit with modern techniques, i.e. with the help of some old paper and matches. It burnt for 93 min, after which the remaining embers were extinguished. After only six minutes of burning, the middle of the fire reached 854 °C. At 12 min, the fire reached the highest IR thermometer measured temperature, i.e. 873 °C in the middle. The highest known temperature from the heat camera recordings of this fire was 1100 °C after 37 min of burning (Fig. 3, Table 1). The direction of the flames was approximately 40° NE and there was a slight NW wind. In the 19th minute, the highest temperature outside the fire was 530 °C, in the direction of the flames. The sediment under the middle of the fire was also measured, but the result might be affected by the moving flames. Here, the highest temperature was 673 °C.

2.2.3. Fire 2

This fire was built from oak wood on sediment with a residual heat of 54 °C, started with the help of matches and papers and was about the same size as the first fire. After 90 min, it was again extinguished and dismantled. Although, the average temperature in the middle was between 950 and 1000 °C, the maximum temperature, 1100 °C, was measured after 75 min (Fig. 3, Table 1). There was some breeze at this point. The direction of the flames was approximately 119° SE, the wind remained NW.

2.2.4. Fire 3

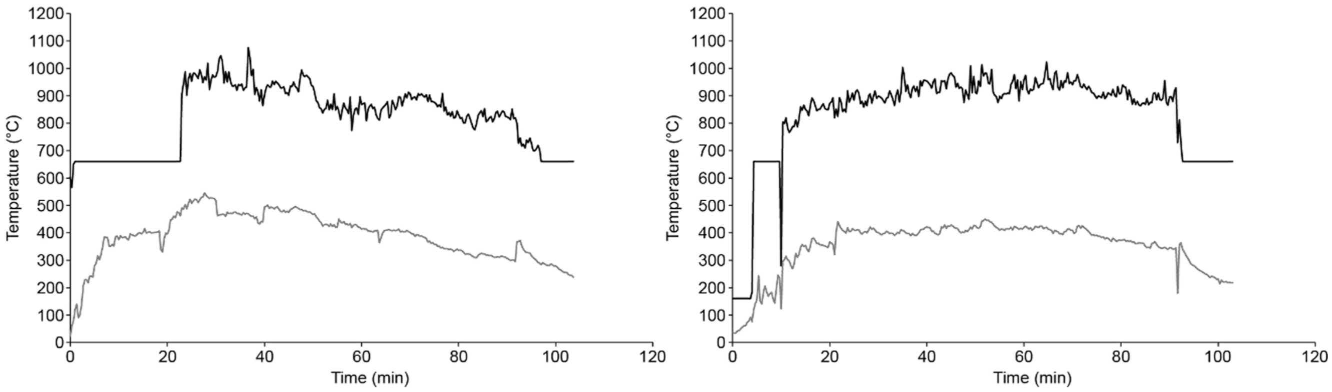
For the third experiment, a mix of oak and pine wood was used for the fire of similar size as in the previous experiments (c. 56 cm). Charcoal and ember from the previous pine fire were used as a base for the fire. This caused that flames started from their own, no additives were necessary. After less than 5 min, the flames' temperature was around 750–800 °C, and 1000 °C was reached after just 5 min. 1100 °C was its hottest measured temperature at 6 and 15 min of burning (Fig. 3, Table 1). After the first hour, the surrounding sediment was 165 °C, the ash below the fire was 400 °C, and the middle of the fire was 925 °C. The burning stopped after about 90 min, when the remaining embers were taken apart. The weather conditions were similar to the previous fires, i.e. a NW wind direction and NE flame direction.

2.2.5. Fire 4

The fourth fire was also composed of oak and pine wood and about 56 cm diameter in size, but this time fresh red deer bones were added as fuel as well. Two whole legs (femur and tibia) and two shoulder bones (scapulae) were used in this fire. The fire was started with the help of matches and papers. Not all bone started to burn immediately. After 10 min, bones that were not on fire yet had a temperature of 50–60 °C and the burning bones were 200 °C. At the same time, the wood on top of the fire was 350 °C and in the middle 908 °C was measured. This fire reached 1000 °C at its hottest after 21 min (Fig. 3, Table 1). After 75 min, white ash in the direct vicinity of the fire was 350 °C, burning bones were still 200 °C, burnt bones at the bottom of the fire were 500 °C, the brownish ash around them was 350 °C, and the wood on top was 130 °C. After 140 min, the fire was taken apart. At this moment, not all the bones were fully burnt. The ones not fully burnt were around 150–200 °C and the fully burnt ones were around 280–570 °C. The sediment at the corner of the fire in the direction of the flames was 160 °C, while the

(a) fire 1 - pine

(b) fire 2 - oak



(c) fire 3 - mixed wood

(d) fire 4 - mixed wood with bones

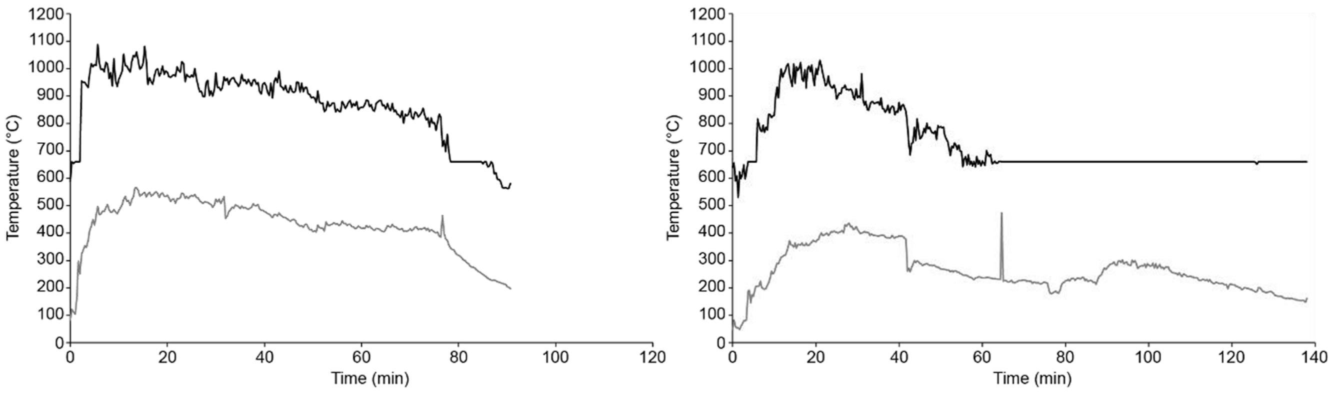


Fig. 3. Graphs of mean and maximum temperatures of the four trial fires recorded by the heat camera.

surrounding sediment was 70 °C. The weather conditions were still similar as the previous fires, with NW wind and NE flames.

2.2.6. *Fire 5 with geological stone samples*

In total, 138 geological samples of different stone types were placed on the surface of the sand before the fire was built. Comparable raw materials were chosen to those found on the Mesolithic sites, consisting of four types of flint and Wommersom quartzite (Table 2). The flint types were collected from different Upper Cretaceous lithological units in Belgium and France; except for the Vlissingen flint, which was retrieved from the North Sea beaches in the Netherlands. The Wommersom quartzite was collected at a place called 'the Steenberg' in Wommersom, Belgium. The latter was also a typical raw material used during the Mesolithic period in Belgium and the southern Netherlands (Perdaen et al., 2006; Cnudde et al., 2013). These raw material types are also part of an interdisciplinary characterisation study (Fiers et al., 2019). More details on the sampling locations can be found in Fiers et al., 2019. From every raw material, three specimens were scanned with high-resolution computed tomography (micro-CT) to gain a good understanding of the structural change after burning. More details on this were published in Fiers et al., 2020.

The 1 m by 1 m square, where the river sand was placed, was divided into 25 cm by 25 cm units. Starting from the middle, three circles were drawn with 15 cm, 37 cm and 45 cm radius (Fig. 4). On these circles, five points were marked out in an equal distance from each other (point C - point R). A line was also marked out through the middle, parallel to the grid. This line was divided into two sections: a section to the left (line A) and a section to the right (line B) (Fig. 4). The specimens scanned with micro-CT were placed as following: one piece from every raw material at the middle (point C), one at 15 cm (point D), one at 37 cm (point E), and one at 45 cm (point F). The points were chosen because they were the most visible for the heat camera, which enabled a continuous recording of the temperature change of the flint pieces. Five pieces from every flint type and one WSQ flake were placed at point C. At every other point, a flint flake of each variant was placed, and additionally at point D, E, G, and P, one WSQ flake. At line A, 27 SHA samples were lined up in the way that they formed a continuous line without hiatus. At line B, the same procedure was followed with HAU flint, including 19 specimens (Fig. 4). After placing the samples and documenting their position, the fire was built. The fire extended over the 15 cm circle and therefore, points C, D, P, M, J, and G were in direct contact with the fire, while points E, Q, N, K, H, F, R, O, L and I were outside of the fire. For line A, 15 samples were in direct contact with the fire; the sample SHA16 was at the edge of the fire. For line B, 16 samples were in direct contact with the flames; sample HAU17 was at the edge of the fire.

We used 5.3 kg oak, 5.2 kg pine and 5.3 kg bones (cow femur) to build the fire. It burnt for four hours. After 7 min, the temperature already reached 939 °C, which reduced to 930 °C 2 min later. The flames directed towards point N, O, K, L.

Until 96 min, the temperature stayed above 500 °C to reach a maximum of 1000 °C at 44 min (Table 1). But even after 155 min, we measured 600 °C as maximum temperature, although the average was around 300–400 °C. This fire was lit on a fresh, air temperature sand with matches and paper. The sediment and ash at the bottom of the fire was around 600–700 °C at 46 min and dropped to 550 °C after 125 min. The weather conditions were similar to the previous four fires, i.e. sunny with occasionally some breeze.

After the fire died out and the sediment cooled down, the samples were collected by hand and the sediment was excavated with a trowel in a 25 cm by 25 cm grid. The sand was collected according to the grid system and sieved on a 5 mm by 5 mm mesh.

2.2.7. *Fires 6 and 7 with experimental lithic tools and geological samples*

Based on the above-mentioned trials, two additional fire experiments with used stone tool replicas were conducted (Appendix A). The replicas were made from the above-mentioned flint raw materials (Table 2) with authentic knapping tools (hard and soft stone hammers and antler punches) to replicate prehistoric stone tools. They were used to replicate Mesolithic activities. One fire was built with pine (fire 6) and the other one with oak (fire 7) wood as fuel. Contrary to fire 5, no bones were added to these fires, since the former indicated that temperature has more impact on stones than the duration of heating. This was also confirmed by experiments in a muffle furnace (Fiers et al., 2020). In addition, fire 5 yielded a considerable amount of burnt bone residue that stuck to the surface of many flint flakes, which was not possible to fully remove (Fig. 5). This impact would probably make it impossible to analyse microwear traces. Therefore, this had to be avoided for the burning experiments of the experimental tools.

Stone tools used on hard material (i.e. bone and antler) and on soft material (i.e. ivy and hazel bark) were put in the fires. The two types of wood fuel, pine and oak, were used separately to have a better reconstruction of the different time periods, namely pine for the Early and oak for the Late Mesolithic. In the trials, it was observed that the burning of both fuels is quite similar; therefore, the comparison between contact materials should be possible. The layout for both fires slightly differs from fire 5. In that experiment, it was noticed that the difference in influence by the fire from 0 to 15 cm and 15–37 cm is too large and at 45 cm the tools did not reach a high enough temperature to have any effect. Therefore, reference points were appointed with a shorter distance in between them and the furthermost point was at only 38 cm from the centre of the fire (Fig. 6). At each point, one tool of each flint type was grouped. These groups were placed at 2 cm (A; middle of the fire), 8 cm (B), 16 cm (C), 26 cm (D) and 38 cm (E) from the centre of the fire in a straight line (Fig. 6). As a continuation of this line, geological samples from the same raw materials were placed at the same distances from the centre as groups of four (one samples of each flint variant), i.e. at point F, G, H, I, and J. WSQ was not included in these experiments because of a lack of sufficiently large raw materials to produce experimental replicas. The fire extended until about the circle at 26 cm, meaning that point A, B, C, D, F, G, H, and I were in direct contact with the fire, while point E and J were outside of the fire.

Fire 6 burnt for 140 min and its size was about 60 cm in diameter. After only 15 min, we measured 850 °C in the middle, which was the highest measured temperature of this fire (Table 1). After 80 min, the fire did not get warmer than 600 °C, and at the 140th minute, the middle of the hearth was 280 °C without any flame burning. The weather was quite cold and the maximum air temperature was 9 °C. The wind speed was minimal and maximum recorded wind speed was 1.7 m/s.

Similarly to fire 6, fire 7 also burnt for 140 min with about the same size as fire 6 (Table 1). This fire reached its highest temperatures after 50 min, i.e. 1000 °C. Moreover, this fire stayed warmer for a longer time and heat only dropped to around 600 °C after almost two hours of

Table 2
List of raw material sources used in this study.

Raw material type	Abbreviation	Geological stage (and period) of host rock	Type of source	Location
Spiennes flint	SHA	Upper Campanian (Upper Cretaceous)	Primary (quarry)	Harmignies, Belgium
Bouvines flint	BOU	Middle/Upper Turonian (Upper Cretaceous)	Subautochthonous (agricultural field)	Bouvines, France
Haubourdin flint	HAU	Coniacian (Upper Cretaceous)	Primary (quarry)	Haubourdin, France
Vlissingen flint	VLI	Unknown	Secondary (North Sea beaches)	Vlissingen, the Netherlands
Wommersom quartzite	WSQ	Ypresian (Paleogene)	Subautochthonous (agricultural field)	Wommersom, Belgium

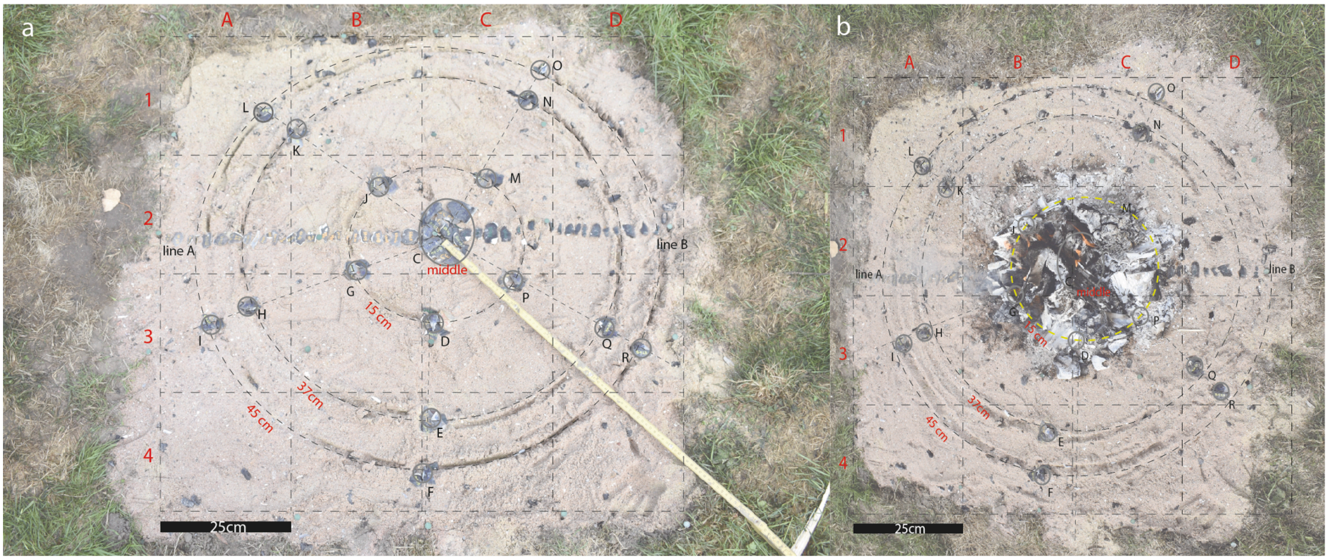


Fig. 4. Layout of the flint samples in fire 5 with indication of the reference points and grid system before (a) and at the end of (b) the experiment.

Fig. 5. Geological flint sample: (a) with burnt bone stuck to the surface, (b) with remaining bone residue after cleaning.

burning. The middle of the fire was still around 400 °C after the flames died out. The weather conditions were similar to fire 6, i.e. 9–10 °C air temperature and 1.5 m/s wind speed. A few minutes after the fire died out, it started snowing for a few minutes.

The samples were recovered by hand and excavated with a trowel according to a 10 cm by 10 cm grid. The sand was collected following the grid system and stored for wet-sieving after both experiments.

2.3. *Analysis of heat damage on lithics*

Several physical changes and burning features on the lithic material were recorded and compared. These features are the same as the ones recorded on the flints that were heated in a muffle furnace for laboratory experiments (Fiers et al., 2020), and similar to the ones described by Clemente-Conte (1997). Colour change (CC), fracturing (B), cracking (C), crazing (Z), potlidding (P), scaling (S), lustre change (L), and translucency change (T) were documented (Fig. 7). A more detailed explanation on these structural damages can be found in Fiers et al. (2020); here, the main results will be presented. The colour change was recorded with a spectrophotometer (X-rite SP60 Sphere Spectrophotometer and Konica Minoltacm-600d Spectrophotometer) and is caused mainly by a combined effect of dehydration, oxidation of (mineral) inclusions or organic matter, and/or altered optical properties of the surface (Fiers et al., 2020). Damage such as cracking, fracturing and potlidding is caused by the increased vapour pressure of water in the pores trapped in flint. It furthermore results from the thermal expansion of quartz, and other potentially present minerals, and is furthermore enhanced by the dense microstructure of flint causing the deformation of mineral grains to generate extreme stress at the grain boundaries (Fiers et al., 2020). Crazing mainly occurs on fine-grained flints and appears as very fine fissures on the surface caused by thermal stress, i.e. by the expansion of minerals and formation of microcracks. Scaling is when small parts of the stone fall off in between crazing fissures and caused by the same thermal stress. Lustre change causes a more waxy appearance and this is best observable on flake scars and ventral surfaces of potlids removed after heating. A decrease in translucency is probably due to the formation of microcracks and general dehydration of the material.

3. Results

3.1. *Fires 1–4*

Even though the different fires were terminated with some help because of time issues, the data recorded with the heat camera clearly shows that there are differences in obtained overall maximum temperature, average temperature and duration of burning between the fuel types (Fig. 3). This was already observed in previous hearth experiments (see Aldeias, 2017 for more reference). However, as it was mentioned before (2.2.1 Methods), the two wood types used in the present study, pine and oak, were neither compared to each other, nor mixed in these previous experiments. As these wood types were important tree species

Fig. 6. Layout of fire 6 and 7 with indication of reference points and distance from the middle. a) Position of experimental tools and geological samples before the fire was built. b) Position of experimental tools visible for the heat camera during burning.

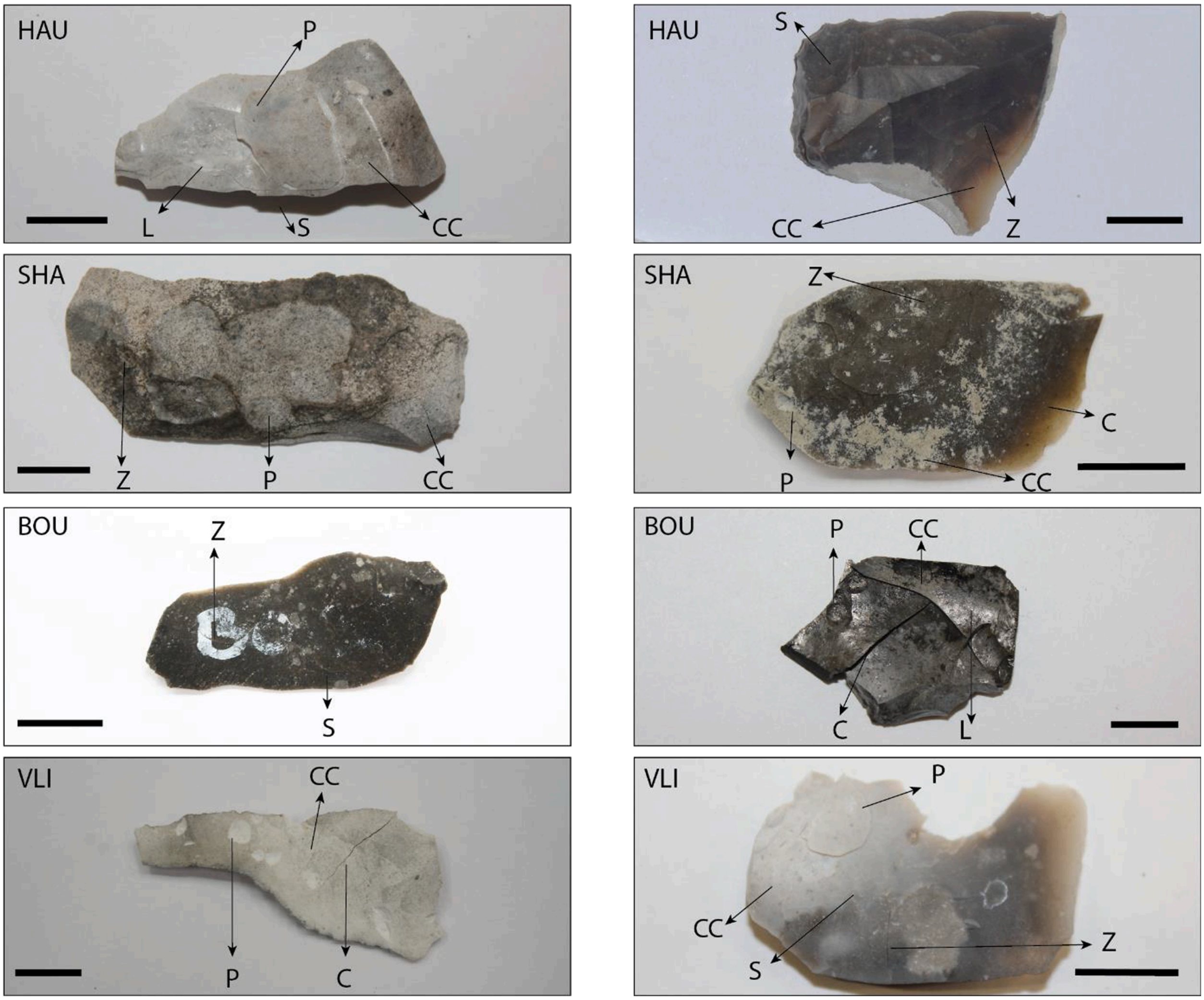


Fig. 7. Examples of heat alteration features. CC: colour change; C: cracking; P: potlidding; Z: crazing; S: scaling; T: translucency change; L: lustre change. Scale bar represent 1 cm.

in our research area during the Mesolithic, as well as in other areas within NW Europe (Bishop et al., 2015), it was important to use these to create an experimental setting resembling prehistoric scenes. Although, previous studies have already shown that the type of wood only has a limited effect on the characteristics of the fire (Henry et al., 2012), the state of the wood has a greater impact. Within our experiments, however, the state of the different firewoods was similar, i.e. both wood types were dried for more than 2 years and the size of the trunks was also similar. This could explain the similar behaviour in fire characteristics between the two types of wood in our experiments (Fig. 3). Even though, the oak fire probably would have burnt longer if it would not have been deliberately extinguished. The mixed wood fire reached the highest temperatures, but burnt for the shortest amount of time without interference. With the addition of bone, the duration of time for the fire considerably increased, but the highest temperature was lower than the oak and the pine fires. The average temperature was the lowest within the bone-induced fire (maximum 732 °C, mean 263 °C), and the highest in the mixed wood fire (maximum 873 °C, mean 427 °C) (Fig. 8). The mixed wood fire reached the highest temperature and was the fastest one to burn down; the temperature increased the least with the oak. After considering these results, we chose a mixed oak and pine fire with the addition of bone to burn the geological stone samples.

3.2. Fire 5

In the fifth fire, lithic raw material was incorporated and the burning resulted in several heat alteration features on the lithic material. The different raw materials reacted in a similar way to the heating (Fig. 9). However, there were some important observations related to the diverse characteristics of the flints. For example, crazing mostly occurred on the HAU flint samples and the SHA samples were more prone to potlidding. Scaling did not occur on the BOU flint, and was only minimal on SHA flint. The translucency of the BOU flint samples changed the least. Colour change showed a very similar pattern in all raw materials. BOU flint seemed to be the least fragile, HAU flint fractured a bit more, and the SHA and VLI flint types had the highest number of broken samples. In general, a lustre change was present on most samples, i.e. 94% of the retrieved samples had gone through this process. The least occurring phenomenon was scaling; this only appeared on 9% of all samples, and most importantly on the HAU flint samples (19%) (Fig. 9).

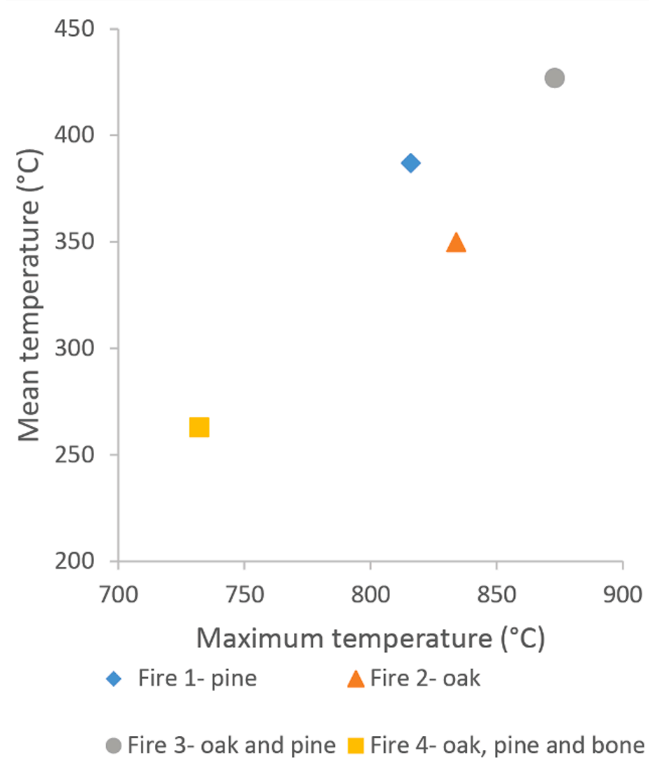


Fig. 8. Relation between mean and maximum temperatures of the first four fires.

The WSQ samples mostly remained intact except for the one specimen that was in the middle of the fire. Colour change occurred in four out of five samples, but in contrast to flint the colour changed to reddish on lower temperatures and to completely black on higher temperatures. From the other physical changes, only crazing and lustre change was visible on the specimen that was positioned in the middle of the fire.

3.3. Fires 6 and 7

The same physical changes were recorded for the lithic samples burnt in fire 6 and 7 (Fig. 10). In general, colour change (89%), cracks (87%), and lustre (81%) were the most present features. Translucency (68%) and fracturing (58%) affected more than half of the specimens. A similar behaviour between the different raw materials was observed when comparing the heat alteration features with the lithics burnt in fire 5. For example, crazing again mostly appeared on the HAU specimens (76%). However, potlidding (11%) was very limited on this raw material. The cause of this still has to be understood. In comparison to fire 5, a higher proportion of SHA samples displaying potlidding (71%) and scaling (86%) was observed. The translucency of BOU changed the least again. In general, just as in fire 5, a colour change occurred on 82–93% of the burnt samples. When looking at the fracturing, it is interesting to see that the trends differ a bit from the trial samples. In general, fracturing happened more often. While the HAU samples broke less frequently (35%), the BOU samples demonstrated to be more fragile (63%). Generally, breakage still occurred the most on the SHA and VLI flint samples (Fig. 10). In comparison with fire 5, we can conclude that maximum temperature is more important in the appearance of the heat alteration features (Figs. 9, 10, 11) than the duration of the heating, as fire 6 and 7 were considerably shorter, but reached similar temperatures (Table 1).

Based on the combination of the above-mentioned thermal features, the experimentally burnt specimens were grouped into three classes: i.e. weakly, medium, and heavily burnt specimens. These terms are used commonly in archaeology (cf. Sergant et al., 2006). By connecting the appearance of the burning features to the position of the sample in the fire, it is clear that immediate contact with the fire is necessary for all features to develop (Fig. 11). The differences between the raw material types are more pronounced, when features are looked at separately. Colour change, lustre change, and cracking were the most frequently occurring features at all distances. From the combination of all the features, it is clear that from the middle of the fire to 15–16 cm, nearly all lithics (80–100%) were burnt heavily, while at 26 cm, heavily burnt artefacts did not occur at all. At that distance mainly medium and to a lesser extent weakly burning occurred. This is due to the much lower temperatures (mean T = 145 °C) at the hearth-periphery compared to the hearth centre (mean T = 690 °C). Outside of the fire, i.e. at 37–38 cm and 45 cm, samples did not get altered at all, as temperatures dropped to 184 °C at 37 cm from the middle of the fire and no direct contact with the fire occurred.

4. Discussion

The described experimental settings are general, implying that they can be reproduced with any kind of lithic raw material. The results of this study show that there is a specific set of thermal alteration features connected to burning, and that the presence and combination of these features can be linked to the position of the stone artefacts within the hearth and thus the temperature (Fig. 11). The occurrence and development of specific heat alteration features is furthermore related to the

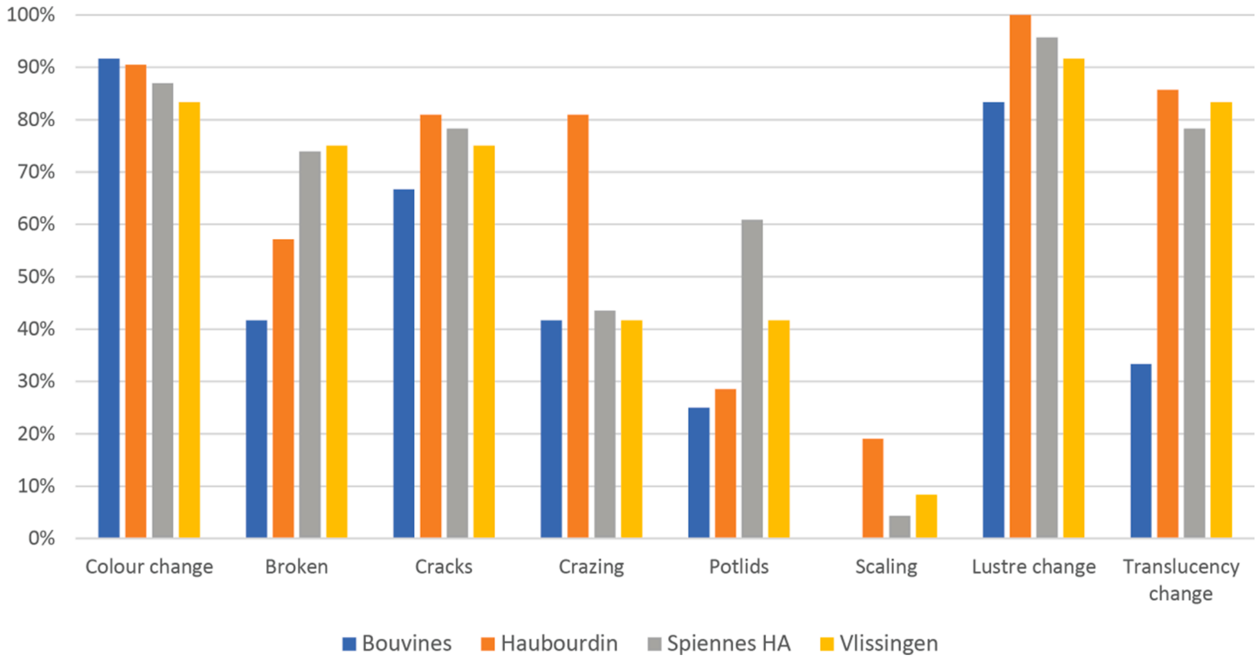


Fig. 9. Ratio of physical heat alterations occurring on the different flint raw materials used in fire 5.

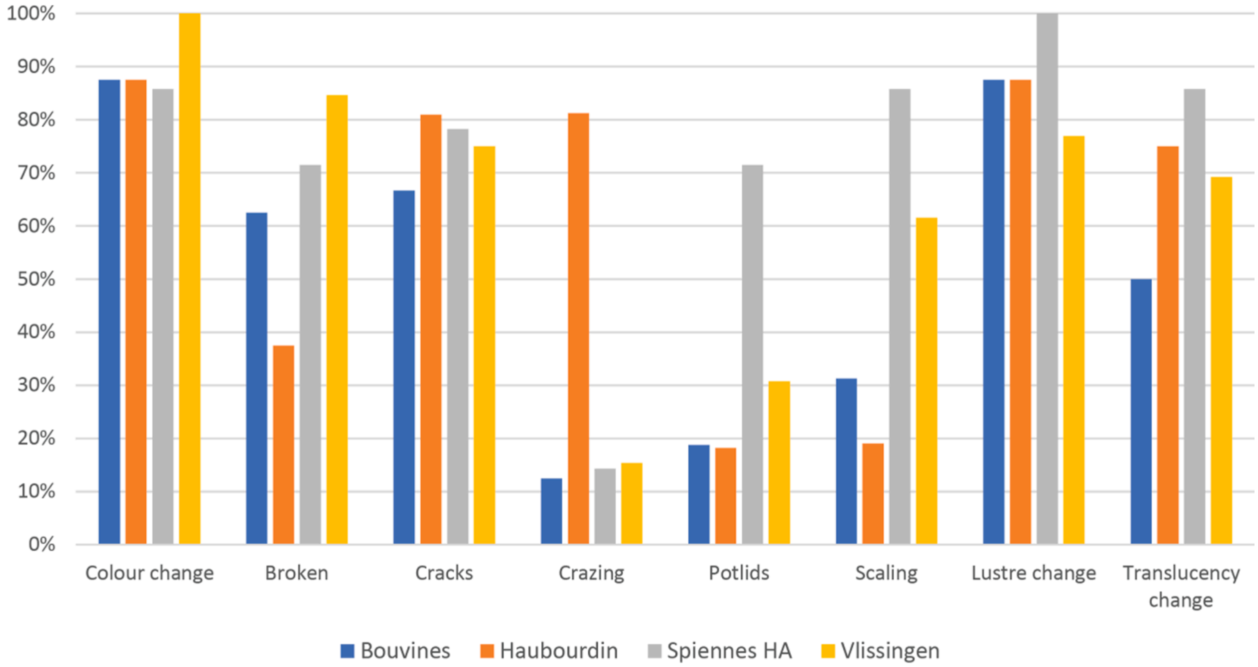


Fig. 10. Ratio of physical heat alterations occurring on the different flint raw materials used in fire 6 and fire 7.

raw material type. This is in agreement with Clemente-Conte (1997), who also observed a different alteration behaviour between different kinds of flint. Moreover, the same alteration features that were described by Clemente-Conte (1997) were observed in our set of samples. This seems to be not fitting with Rutkoski et al. (2019), who only observed fracturing, but they also only experimented with one flint type. This underlines the importance of the raw material characteristics in the development of thermal alteration features. Further research should be conducted to investigate a larger range of raw materials, as suggested by Rutkoski et al. (2019) as well.

By performing these experiments, we gain a better understanding of the behaviour of Mesolithic communities. First of all, they provide a base for reconstructing possible scenarios concerning the relationship of people to their stone tools and to their fire places. Moreover, the experiments also give us a firm background on the interpretation of burnt tools, through which we gain a better grasp of the daily life or even social organisation of Mesolithic hunter-gatherers.

Fig. 12a demonstrates clearly that direct or intermediate contact with the fire is absolutely necessary to have some degree of burning. This is due to the fact that the temperature drops rapidly outside of the fire, as was demonstrated by all experimental fires.

The observation that contact with fire is necessary for burning features to develop gives the opportunity to interpret the ratio of burnt lithics from archaeological sites in more detail (Fig. 12). Fig. 12(a)

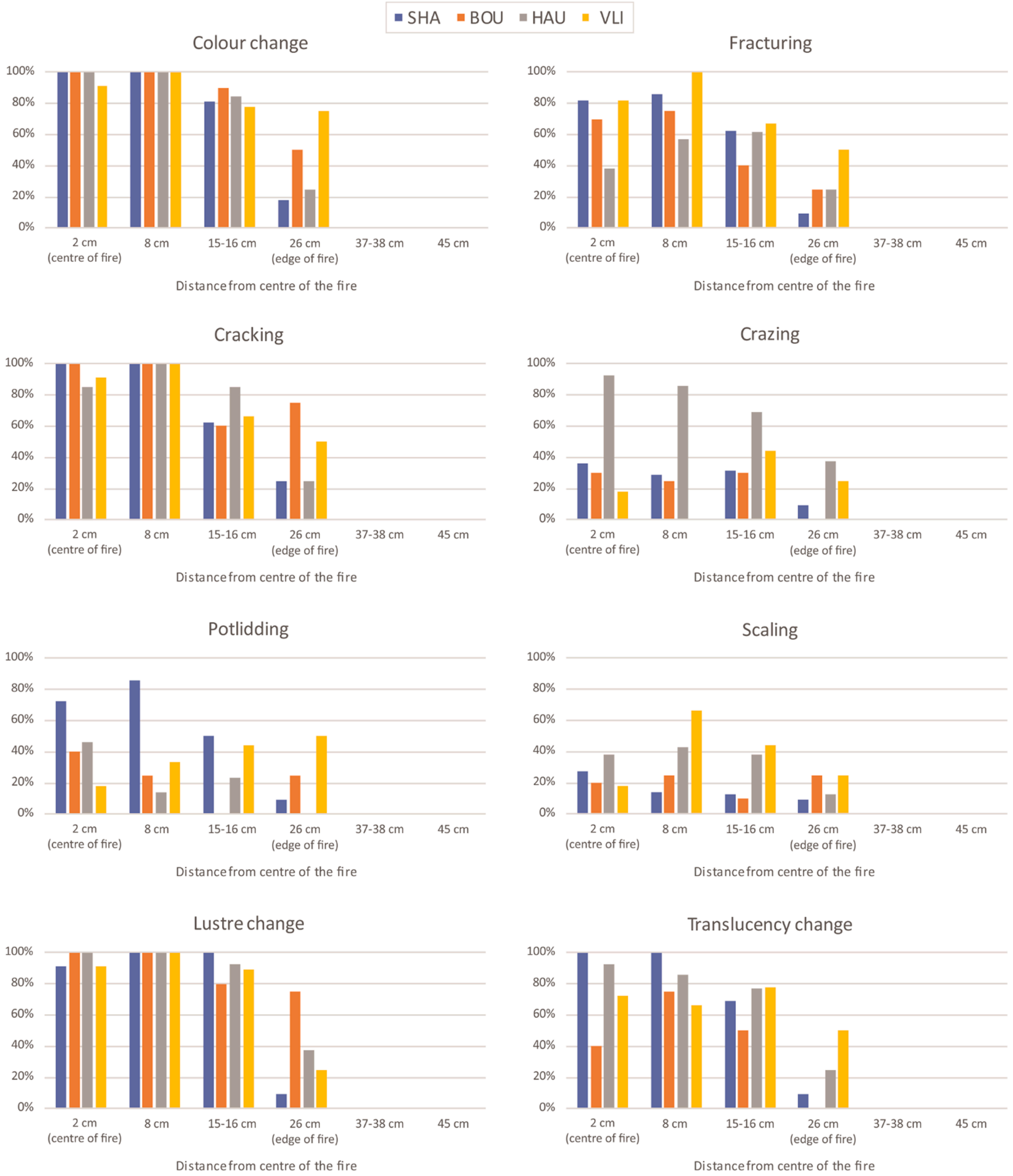


Fig. 11. Connection between position in the fire and appearance of alteration feature by raw materials based on fire 5, 6 and 7. The position correlates to the maximum temperature, i.e. highest temperatures were measured in the middle of the fire and temperatures are decreasing with larger distance from the centre.

illustrates the proportion of weakly, moderately and heavily burnt lithics in our experiments with respect to their position in the fire, while Fig. 12(b and c) document the amount of burnt lithics by degree of burning per individual concentrations (lithic locus) on two early Mesolithic sites (Kerkhove-Stuw and Verrebroek Dok1) from the Scheldt valley. Comparison between both sets of data (Figs. 12 and 13) allows us to formulate a number of interesting observations. Firstly, comparison between the experimental data and the archaeological data from Kerkhove demonstrates a good agreement on the level of weakly burnt artefacts. In both sets these are hardly present (<10%), suggesting that deliberate heat treatment was not applied on the studied Mesolithic sites. Alternatively it could point to the fact that only few artefacts were

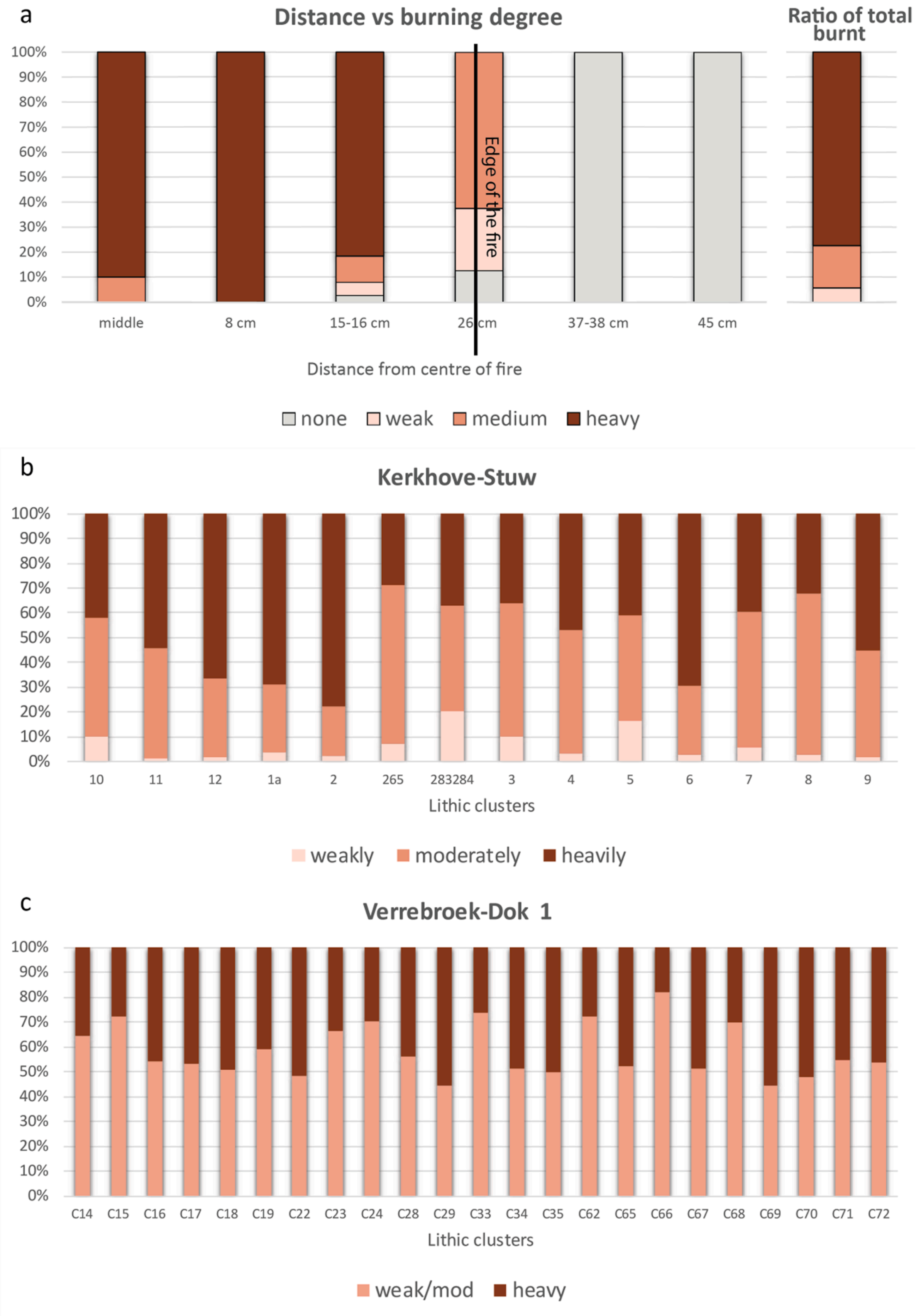


Fig. 12. Comparison of different burning degrees in experimental and archaeological fires. a) Ratio of burning degrees displayed by distance from the centre of the fire and as total. b) Ratio of burning degrees per individual artefact cluster/hearth area at Kerkhove-Stuw. c) Ratio of burning degrees per individual artefact cluster/ hearth area at Verrebroek-Dok 1.

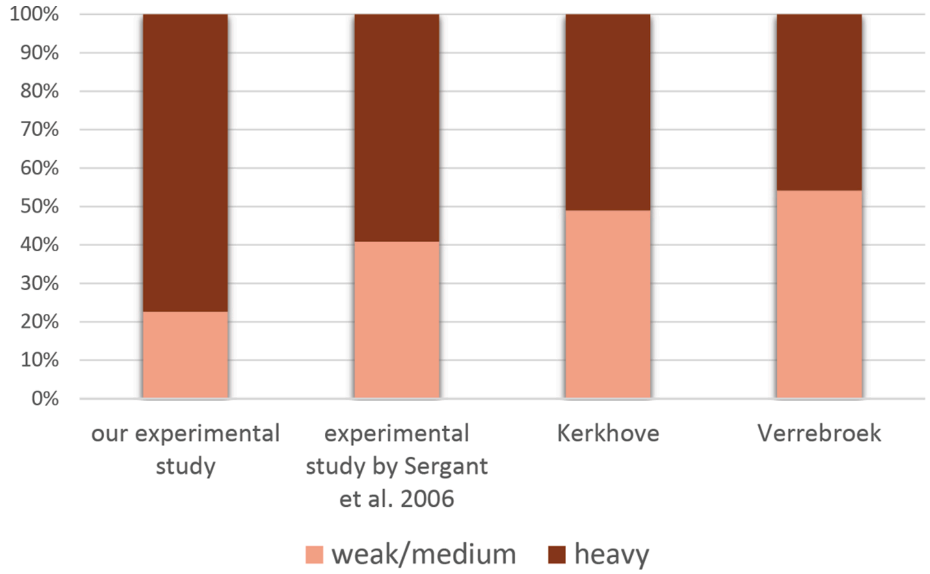


Fig. 13. Relative ratio of burning degrees on lithic material in the experimental studies (our study and Sergant et al., 2006) and archaeological collections, Kerkhove and Verrebroek.

not in direct contact with the fire, as they were either situated at the periphery of or below the fires, under a few centimetres of sediment. On the other hand there seems to be a clear difference between the experimental and archaeological data with respect to the moderately burnt artefacts (Figs. 12 and 13), i.e. proportions reaching ca. 20% versus ca. 40–50% for experimental and archaeological data, respectively. This marked difference probably refers to differences in hearth setting. It might imply that a larger portion of the lithic assemblage on prehistoric camp-sites was situated around the edge of the hearths and less in its centre. If so, this might indicate that part of the burnt lithics ended in the hearths by accident, e.g. during knapping or other activities performed in the direct vicinity of the hearths. Yet, it needs to be stressed that the results of our experiments are not fully in line with those performed by Sergant and colleagues (2006). The latter resulted in a somewhat higher proportion of weakly/mediumly burnt artefacts, i.e. up to ca. 41%, which is closer to the prehistoric data (Fig. 13). This marked difference between both experimental projects probably results from major differences in their settings. Contrary to our experiments, Sergant et al. (2006) opted to throw artefacts into the hearths during the burning process. Due to the thermal shock quite some artefacts exploded, which led to the ejection of mainly potlids from the hearth as far as 2.5–3 m. Interestingly, none of these ejected artefacts were heavily burnt. In our experiments, ejection of artefacts out of the fire was not observed probably due to the fact this process was hindered by the firewood lying on top of the artefacts, explaining the smaller proportion of weakly/medium burnt artefacts. So, the closer correspondence between the experimental data from Sergant et al. (2006) and the prehistoric data might point to artefacts getting burnt as they accidentally ended up in hearths during peripheral, hearth-related activities. Of course, it cannot be fully excluded that part of the burnt artefacts on prehistoric sites got affected because a fire was lit on top of them, especially with larger quantities of heavily burnt artefacts in lithic clusters. This scenario is to be expected on sites or lithic clusters with evidence of re-use, so called cumulative palimpsests (Bailey, 2007). Several Mesolithic sites, such as Howick and Mount Sandel in Northern Ireland, have provided proof of repeated usage of the same fireplace or a location for fireplaces (Mithen, 2019). Finally, it should also be considered that the observed differences between our experimental data and the archaeological data might be related to differences in fire intensity. Our experiments clearly demonstrated that the maximum temperature has more impact than the mean temperature, and that the former shows considerable differences according to the used fuel. Some prehistoric hearths might thus have reached lower temperatures than our experimental hearths, producing less overheated artefacts as these only appear when fire temperature is higher than at least 500 °C (Fiers et al.,2020). This hypothesis might be valid for the Mesolithic site of Kerkhove (Vandendriessche et al., 2019), as on this site most animal bones found in the hearths were not fully calcined (T > 600 °C), but displayed a brown to black colour (so-called charred bones). According to recent experiments (Pérez et al., 2017), the latter is typical for bones either buried under a hearth or lying over embers but not in the full flames. On the other hand, at another Mesolithic site in the Scheldt basin, Verrebroek "Dok 1", all animal bones are fully calcined, indicating direct contact with high temperature fires. Therefore, we probably deal with different or even mixed scenarios. This makes the broader socio-economic interpretation of our findings even more complicated. This might be addressed by a new experiment: a repeatedly used hearth on the same spot over a longer time period with different actions to introduce stone artefacts to the fire, i.e. burying them under the sediment, throwing them, and putting them under the fire as it was done in the described study. On the other hand, higher resolution archaeological data could also provide more insight.

5. Conclusion

By combining scientific methods and experimental archaeology, we gained a well-founded understanding of the factors affecting fire characteristics and the influence of these characteristics on different raw materials. This paper has argued that it is important to understand the burning circumstances of lithics in order to interpret them. Therefore, we need a thorough study of both fire and stone characteristics with interdisciplinary techniques. Our experiments showed, in agreement with previous experimental studies (e.g. Purdy and Brooks, 1971; Mercieca and Hiscock, 2008; Prinsloo et al., 2018), that burning features depend on many factors, going from maximum temperature to the structural properties of the raw material. One of the more significant findings to emerge from this study is that there are important differences among various raw material types. These differences can clearly influence the interpretation of tools made of specific flint types, e.g. the intensity of burning and the maximum temperature at which they were burnt, as different raw materials start showing specific heat alterations at different temperatures and the set of physical changes also vary depending on the raw material (Fiers et al., 2020).

These results are valuable not only in the interpretation of the Mesolithic sites studied in our project, but also in the research of other time-periods in which flint was used, as well as in the wide geographical region in which these raw materials were part of the material culture. In a broader sense, our unique methodology can be implemented in any archaeological and geological investigation that concentrates on stone, especially the heating of lithic material.

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Appendix A

Overview of sample size and weight (average ± standard deviation) of the raw materials burnt in the campfire experiments. For fire 5, only geological flakes were used. For fire 6 and 7, 5 geological flakes and 5 experimental tools were used for each raw material per fire.

Raw material type	Number	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)
Fire 5					
SHA	50	4.30 ± 5.12	34.7 ± 12.27	21.60 ± 6.75	5.59 ± 2.73
BOU	23	3.86 ± 3.20	31.90 ± 4.86	21.04 ± 6.41	7.22 ± 3.39
HAU	42	3.42 ± 3.63	32.19 ± 8.15	20.80 ± 6.22	5.66 ± 2.47
VLI	23	6.92 ± 8.14	38.64 ± 10.22	24.98 ± 7.94	7.69 ± 2.59
WSQ	5	5.13 ± 4.90	30.16 ± 4.97	21.41 ± 8.79	8.16 ± 2.64
Fire 6					
SHA	10	3.74 ± 3.31	38.06 ± 12.00	21.28 ± 7.67	4.50 ± 1.92
BOU	10	7.04 ± 6.23	39.20 ± 11.81	24.62 ± 6.71	7.81 ± 3.31
HAU	10	13.76 ± 17.18	49.80 ± 17.40	26.65 ± 6.59	9.14 ± 6.32
VLI	10	5.43 ± 4.92	37.99 ± 14.26	23.95 ± 7.63	8.03 ± 6.18
Fire 7					
SHA	10	8.95 ± 6.93	43.88 ± 11.66	25.61 ± 5.39	7.63 ± 2.57
BOU	10	7.73 ± 6.33	39.37 ± 7.50	27.65 ± 8.35	8.36 ± 3.70
HAU	10	6.47 ± 6.11	38.20 ± 11.19	23.66 ± 7.78	6.35 ± 2.65
VLI	10	5.87 ± 4.86	31.31 ± 7.70	23.32 ± 7.14	6.54 ± 3.79

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