FINDING PROMETHEUS: EVIDENCE FOR FIRE IN THE EARLY PLEISTOCENE AT FXJJ20 AB, KOOBI FORA, KENYA.

By

SARAH HLUBIK

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And approved by

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ABSTRACT OF THE DISSERTATION

FINDING PROMETHEUS: EVIDENCE FOR FIRE IN THE EARLY PLEISTOCENE AT FXJJ20 AB, KOOBI FORA, KENYA.

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Dissertation Director:

Craig S. Feibel

Fire use by early hominin ancestors has caught fire in the academic and popular imagination. Discussions over what constitutes control, what evidence is appropriate, and how we interpret evidence within sites have contributed to a rigorous debate over when hominins began to exploit and rely on fire as a cultural tool. Physical evidence from *Homo erectus* indicates a major shift in behavior around 2 million years ago (mya); *H. erectus* is taller than previous hominins, with smaller teeth, a smaller gut, and a larger brain. These morphological changes indicate a behavioral change to a higher quality diet with greater energetic return, which could have been achieved by cooking both plant and animal foods. Many debates about early fire have centered around the paucity of sites in the early archaeological record, between 2 and 1 mya, as proof that fire was not significant to humans until about 350 thousand years ago (kya), when near-modern ancestors were prevalent throughout the globe, and archaeological evidence for fire is much more common. Some researchers have begun looking for evidence in earlier sites to determine whether fire was present and in what capacity. The issues surrounding the recovery and identification of fire evidence from early sites include the number of unprotected, or open-air, sites, and the lack of knowledge surrounding the diagenetic processes that could be affecting fire

evidence. This dissertation details the work done at FxJj20 AB, a site in Koobi Fora, Kenya, dated to 1.6 mya, with potential evidence of fire use in the Early Pleistocene. The work includes a number of experiments to establish a baseline of what types of evidence might be present from the lithic material and sediment unique to the site, meticulous excavation of the site itself with extensive sampling for Micromorphological geological analysis, and Fourier Transform Infrared spectrometry (FTIR); Micromorphological analysis is used to look at the integrity of the site as well as to evaluate fire evidence, while FTIR is used to investigate the thermal history of recovered materials. Spatial analysis of the recovered materials from the site is used to show clustering of materials and interpret associations, and orientation analysis is used to determine whether there is evidence for movement of materials by water or other geological processes. The results of the work done here show that fire was present on the site, and indicate that this fire was associated with the hominins occupying the site. FTIR identified over 40 instances of burnt bone and sediment, and spatial analysis showed these burnt materials were clustered within the largest cluster of lithic materials on the site. Orientation analysis indicated no movement of materials by water, and the burned and unburnt materials are mixed in the vertical dispersion. Together this indicates that the evidence for fire on FxJj20 AB is associated with hominin behavior and is likely the result of hominin-controlled fire.

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Chapter 3 of the dissertation has been submitted for publication and is under review in the *Journal of Human Evolution*, to be part of a special issue on research in Koobi Fora of the Okote

Member. The list of co-authors is: Sarah Hlubik, Russell Cutts, David R. Braun, Francesco Berna Craig Feibel, John W.K. Harris.

Chapter 4 of the dissertation has been prepared for submission to the *Journal of Archaeological Sciences* and is being submitted for review. The list of coauthors is: Sarah Hlubik, David Braun, Francesco Berna, Craig Feibel, Russel Cutts, John WK Harris

S. Hlubik is the primary author of the papers that have been submitted, or will be submitted, and has done the bulk of the writing with some contributions from the coauthors.

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Chapter 1. Introduction to the Dissertation

The timing of the initial controlled use of fire is an important but controversial topic. Fire-use by hominins may explain the morphological changes seen with *Homo erectus* ca. 1.9 Ma (Aiello and Wheeler, 1995; Wrangham et al., 1999; Aiello and Wells, 2002; Wrangham and Conklin-Brittain, 2003; Carmody and Wrangham, 2009), yet widely-accepted archaeological evidence for fire use is absent prior to 1 Ma (James, 1989; Sandgathe et al., 2011; Wil Roebroeks and Villa, 2011). A handful of sites dated earlier in East and South Africa claim to have evidence for hominin use of fire (Gowlett et al., 1981; Harris, 1982; Clark and Harris, 1985; Brain and Sillen, 1988; Brain, 1993; Ludwig, 2000; Berna et al., 2012) but in every case the evidence has been questioned. Current evidence for early hominin fire use is sporadic as well as temporally and geographically dispersed (Clark and Harris, 1985; James, 1989; Wil Roebroeks and Villa, 2011; Shimelmitz et al., 2014), but no unequivocal study for Early Pleistocene fire use has been recovered.

1.1 Background to the Dissertation

1.1.1 Evolutionary Evidence for Early Fire Use

Discussions in the 1980s suggested that cooking, would have allowed for a major increase in the breadth of plant foods that hominins could consume (Leopold and Ardrey, 1972; Stahl et al., 1984). In 1999, Wrangham (1999) hypothesized that the evolution of *H. erectus* was dependent on the incorporation of cooked foods in the hominin behavioral repertoire. He pointed to the decrease in gut and tooth size and increase in body and brain size as the main support for this hypothesis, arguing that regular use of fire would have relaxed selective pressures for large teeth and guts (Wrangham et al., 1999). The energy needed to maintain metabolically expensive tissues and structures in the gut would then be available for use by other systems (Aiello and Wheeler, 1995). This, coupled with the increase in caloric returns from cooked foods, would enable brain and body size increases (Aiello and Wheeler, 1995; Wrangham et al., 1999; Aiello and Wells, 2002; Wrangham and Conklin-Brittain, 2003; Carmody and Wrangham, 2009).

A higher-quality diet, consisting of more easily chewed food with a higher energy return, would allow for a reduction in metabolically expensive gut tissue, and an increase in metabolically expensive brain tissue in addition to supporting a larger body size (Aiello & Wheeler 1995; Aiello & Wells 2002; Organ et al. 2011). Several researchers have suggested that the acquisition of meat resources was sufficient to result in smaller jaws and guts while increasing brain size (e. g. Blumenschine & Pobiner 2007; Milton 1999; Speth 1989). Persistent carnivory in *Homo* is dated to 2.0 mya (Ferraro et al., 2013) while evidence for acquisition of meat resources dates at least to 2.6 mya (Semaw et al., 2003), and potentially as early as 3.4 mya (McPherron et al., 2010).

Increases in the amount of meat would increase levels of fat, protein, and essential acids in the diet. However, this model ignores that meat digestion increases the basal metabolic rate and water needs (Aiello & Wells 2002), that non-carnivore digestion of protein for energy is inefficient (Milton, 1999), and the dangers of consuming too much protein, particularly lean protein, for energy needs (Cordain et al. 2000; Smil 2002; Speth & Spielmann 1983; Speth 1987). Finally, this argument ignores the potential of consuming parasites and bacteria with uncooked meat (Smith et al., 2015), as well as the tendency of primates to avoid carrion, particularly if they have been made sick by it in the past (Ragir et al., 2000).

The long gap between the introduction of meat resources and evidence of its persistent use suggests that some barrier may have persisted to the regular and persistent incorporation of meat in the diet. Prior to the ability to hunt, meat from large game would need to be scavenged, but parasite and bacterial loads would have made this a risky resource (Ragir et al., 2000; Smith et al., 2015). The introduction of fire into the behavioral repertoire would have reduced the pathogen loads in meats (Smith et al., 2015) and increased the efficiency of digestion (Boback et al., 2007) thus making meat a viable and valuable resource.

Wrangham and colleagues (1999) put forth the hypothesis that morphological changes see in *Homo erectus* could be explained if *H. erectus* used of fire to help process foods more efficiently. Several studies have supported the increases in caloric return of foods after cooking (Boback et al. 2007; Carmody, Weintraub, & Wrangham 2011; Carmody, Weintraub, & Wrangham 2010). Cooking is the most effective and efficient method of food preparation, increasing the caloric return of both meat and plants significantly over other preparation methods like pounding or grinding (Boback et al. 2007; Carmody, Weintraub, & Wrangham 2012; Carmody, Weintraub, & Wrangham 2010; Carmody & Wrangham 2009). Cooking would have increased the number of foods available to hominins by reducing the number of toxins from plants (Leopold and Ardrey, 1972; Stahl et al., 1984), reducing pathogenic load of scavenged meat resources (Smith et al., 2015), and allowing more regular access to meat resources and thus permitting meat to become a greater portion of the diet.

1.1.2 Archaeological Evidence for Fire in the Early Pleistocene

Several researchers conclude that the evidence for fire use early in the Pleistocene is too sporadic and likely represents opportunistic use of wild fire (e.g. Roebroeks & Villa 2011; Sandgathe et al. 2011). While archaeologically secure evidence for the creation of fire is not found until much later, in the late Upper Paleolithic (Sorensen, Roebroeks, & van Gijn 2014), the possibility of collecting fire from wild sources or creating fire from perishable materials remains extremely challenging to be distinguished in the archaeological record. Nevertheless, understanding the mechanics of fire, being able to capture it and use it to advantage would imply some form of control, and, if wildfire was regularly available, it could indeed begin to make biological changes in the hominins that used it.

The most ambiguous evidence for fire in the early Pleistocene record comes from the sites of Gadeb and the Middle Awash, in Ethiopia (Clark and Kurashina, 1979; Barbetti et al., 1980; Clark and Harris, 1985), and Olduvai Gorge, in Tanzania (Ludwig, 2000). The site of Gadeb 8E is dated between 1.45 and 0.7 Ma and is found in the highlands of Ethiopia (Clark and Kurashina, 1979; Haileab and Brown, 1994). Archaeologists found a number of artifacts made of ignimbrite with differential red and grey coloring, while unweathered artifacts tend to have a brown color (Clark and Kurashina, 1979; Clark and Harris, 1985). Thermoremanent magnetic (TRM) testing of these artifacts is difficult because of their igneous origin. Initial results are consistent with being heated, as opposed to a geogenic origin for this signature (Clark and Harris, 1985). In the Middle Awash research area, in the Bodo stream drainage, a number of patches of discolored earth were identified in Pleistocene sediments associated with Oldowan and Acheulean artifacts (Clark and Harris, 1985). Radiometric (Ar/Ar) dates of this site place the Acheulean artifacts around 0.6 Ma. Oldowan artifacts are found considerably lower in the sequence (Clark et al., 1994). Baked clay dated to the earlier part of the Bodo sequence was generally massive and showed evidence of channels associated with termite mounds. Two of these rubefied features from the Pleistocene were associated with artifacts (Clark and Harris, 1985). The sedimentary features associated with artifact-bearing layers lacked a stone ring and other typical hearth features which, at the time of their discovery, were considered to be characteristic of hearths of human ancestors (Clark and Harris, 1985). However, these rubefied features were round or ‘lozenge-shaped’ in cross section, with variable coloration from yellow to red (Clark and Harris, 1985). The association between hominins and these fire patches was suggested to be evidence of hominins constructing defense structures. The scenario proposed posits that hominins could have used natural occurrences of burning tree stumps or termite mounds as defense against predators (Clark and Harris, 1985). The shape of the burned patches is consistent with the shape of small controlled fires known from experimental and ethnographic work (Mallol et al., 2007).

Swartkrans, in South Africa, dated to around 1.2 Ma, contains evidence for fire in the form of burnt bones (Brain and Sillen, 1988; Brain, 1993). Experimental work has shown that these bones are burnt (Brain and Sillen, 1988), but questions remain as to how the bones came to be in the cave. During an examination of artifacts from Olduvai Gorge in Tanzania and Koobi Fora in Kenya, Ludwig (2000) found evidence of thermal alteration on a number of artifacts. Ludwig identified features that are consistent with those documented in stones exposed to temperatures over 480^{o}C. Ludwig noted that these features of the Olduvai record appear frequently in sites that are 1.5 Ma, but sites older than this show none of these characteristic signs of heating (Ludwig, 2000). Ludwig interpreted this as evidence that fire was present and widespread by 1.5 Ma (Ludwig, 2000). Currently the evidence from the Early Pleistocene is suggestive but not conclusive.

One of the most well-known sites that contain evidence of combustion features is the locality of Chesowanja (Baringo Basin, Kenya). Chesowanja has several localities but the site known as GnJi 1/6E, included several baked clay clasts. This site also hosted numerous concentrations of *in situ* stone tools, and bones. The artifacts and fossils were recovered from fine-grained silty clays capped by a basalt which was dated to 1.42 Ma by K-Ar dating (Hooker and Miller, 1979;

Gowlett et al., 1981; Clark and Harris, 1985). One possibility is that the association between the stone artifacts, fossils and features that reflect evidence of combustion are the result of post-depositional processes. Fluvial processes can sometimes concentrate materials that have no behavioral association. A preliminary review of the edges of the stone artifacts suggest they have not been subjected to the types of fluvial transport that result in “hydraulic jumbles” as has been documented in other localities (Schick 1986; Clark and Harris, 1985).

At Wonderwerk Cave, in South Africa, ashed plant remains have been identified in archaeological layers associated with Early Stone Age artifacts (Berna et al., 2012). This horizon is dated to the Jaramillo subchron (~1.0 Ma) by a combination of 10Be/26Al burial ages and paleomagnetism measurements (Chazan et al., 2008; Berna et al., 2012). This finding is significant because caves are less susceptible to the kinds of post-depositional processes that affect many open-air sites. That the ash found in the cave is plant ash suggests that that the material was brought into the cave and burned (Berna et al., 2012). Given the spatial association with the archaeological remains, the researchers propose that the fire features were the result of hominin control of fire (Berna et al. 2012).

The site of Gesher Benot Ya’aqov (GBY), in Israel, has been the subject of the greatest amount of research involving the presence of hominin controlled combustion features (Goren-Inbar et al., 2004; Alperson-Afil and Goren-Inbar, 2006, 2010, Alperson-Afil et al., 2007, 2009; Alperson-Afil, 2008). The excavators of GBY found clusters of burned flint microartifacts (less than 2 cm. in maximum dimension) in areas that they believe correspond to activity areas on their excavation surface (Alperson-Afil et al., 2007, 2009; Alperson-Afil and Goren-Inbar, 2010). This locality, associated with Acheulean artifacts, is placed at the edge of paleolake Hula, stratigraphically located just above the Brunhes-Matuyama paleomagnetic boundary at 780 thousand years ago (kya); (Goren-Inbar et al., 2000). Detailed excavations documented that smaller burned artifacts were found in clusters, which were spatially distinct from larger, unburned artifacts (Alperson-Afil et al., 2007). In addition, the researchers found charcoal in association with the archaeological materials, indicating that fire was associated with the hominin activities at the site (Alperson-Afil et al., 2007, 2009; Alperson-Afil and Goren-Inbar, 2010).

Very few of the sites discussed contain the suite of characteristics often used as unequivocal evidence of controlled fire [i.e. hearth features, ash deposits, charcoal (James, 1989)]. Defining controlled fire has long been an issue in paleoanthropology; some researchers regard control as use and maintenance of fire regardless of whether the source of is collected wildfire or production of the fire itself, while others maintain that true control of fire must be the result of fire that has been produced by humans (Sandgathe, 2017). For the purposes of this study, controlled fire is any fire that can be positively associated with human use, regardless of the potential source. This is primarily because we cannot know whether Pleistocene hominins were creating fire with organic materials, like a fire drill, or collecting it from existing sources of fire on the landscape. Add to this the difficulty of preserving ephemeral and easily disturbed materials such as ash and early, open-air archaeological sites become particularly problematic to study. As a result, it is necessary for researchers to develop novel methods to investigate the presence of fire on these sites. Most importantly, since open-air sites are subject to wildfires, we must determine whether the evidence of combustion features recovered from Pleistocene archaeological sites is, in fact, due to hominin activity and not landscape fires. To do this, we must first collect the evidence carefully, including a rigorous sampling strategy and strict collection guidelines in which all material, no matter how small, is precisely plotted, and then determine what lines of evidence are present on a site (e.g. burnt bone, rubefied sediment, ash remnants, or magnetic anomalies). Once the evidence is collected, we must look at the spatial relationships between burned and unburned materials. Controlled fire will be spatially concentrated, while wildfire would be homogenously distributed throughout the site.

Despite the challenges facing archaeologists to document early fire, many researchers suggest that because the advantages of fire use would be so great, there were strong selective pressures for this behavior (Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Wrangham and Carmody, 2010; Gowlett and Wrangham, 2013). Controlled fire would have provided protection from predators, allowed for the expansion outside the East African Rift Valley, provided an extension of the daylight hours which would have allowed for extended social interaction, and enabled cooking food, opening up new resources and allowing for increased digestion of other resources (Clark and Harris, 1985; James, 1989; Wrangham et al., 1999). Complex behaviors do not preserve archaeologically and researchers are unlikely to determine how fire was used socially, but cooked food, particularly animal foods are possible to identify in the archaeological record.

The presence of fire in the record before 250 kya indicates that the story of how and why our ancestors began using fire in prehistory is complex. This may have far-reaching implications for the biology and physiology of our ancestors, despite the relative infrequency with which it was used. We must ask, if there is evidence for fire at early archaeological sites, why is it so difficult to document hominin use of fire on these sites? Does the evidence found at later sites in the Middle and Upper Paleolithic represent the only acceptable evidence, or do we need to look at other proxies of evidence to document these behaviors at earlier time periods? It is possible that we will need to look for new proxies of these novel behaviors that preserve in earlier time periods.

1.1.3 Fire Evidence at Koobi Fora

The sites of FxJj20 East and FxJj20 Main were discovered in the 1970s (Harris, 1973, 1978). These sites are situated on tuffaceous silts, buried by low energy water bringing in sediments to a floodplain environment (Harris, 1997). The original excavations of this site revealed several rubefied patches of consolidated sediments that the researchers hypothesized may be related to fire use by early hominins (Clark and Harris, 1985; Harris, 1997).

Further investigations by Bellomo (1994) and Bellomo and Kean (1997), reviewed the magnetic signatures and magnetic susceptibility of the concentrations in comparison with the surrounding sediments. Bellomo and Kean (1997) concluded that at least two of the features found at FxJj20 Main indicated that anomalies in the magnetic susceptibility signature had considerably higher remnant magnetic signatures than the surrounding sediments. They interpreted this anomaly as evidence that these patches were combustion features controlled by hominins. Bellomo and Kean (1997) suggested that this pattern was consistent with patterns previously described as single campfires. Although the data from Bellomo and Kean's (1997) study was suggestive that the features at FxJj20 Main and FxJj20 East were reflective of hominin controlled combustion features, the analysis was hindered by weathering processes that occurred on these patches of sediment between the time of their original excavation and their eventual analysis twenty years later. Bellomo (1994) described detailed spatial analysis of the associated archaeological material at FxJj20 Main and East. He concluded that the concentration of material showed patterning that was related to the combustion features. Later, Rowlett (2000) conducted thermoluminescent studies and determined that the patches were heated more recently than the surrounding sediments. He also looked at the phytolith content within the patches compared to the surrounding sediments. The patches showed a mixture of phytoliths identified as grasses and trees, while the surrounding sediment was primarily grasses (Rowlett, 2000). However, the amount of time between the exposure of these patches and the sampling could result in contamination of modern materials within the samples.

1.1.4 FxJj20 AB – A site apart

This dissertation consists of three papers, one published, one in press, and one ready for submission, detailing the research completed thus far at FxJj20 AB. The data present a compelling argument for the presence of fire in the Early Pleistocene at the site. FxJj20 AB is located approximately 150 m north and west of the FxJj20 East and FxJj20 Main sites. The excavations, which took place between 2010 and 2016 during the field seasons for the Koobi Fora Field School, are detailed in the following papers. The analysis methodology included Fourier Transform Infrared (FTIR) spectrometry and microscopy, to look at individual samples and sedimentary thin sections for evidence of fire. Petrographic microscopy was also used for further analysis of the thin sections. The recovery methodology of the excavations allowed for detailed comparisons of the materials recovered to experimental collections of stone knapping activities, as well as for detailed spatial and orientation analysis.

The first paper (published), “Researching the nature of fire at 1.5 mya on the site of FxJj20 AB, Koobi Fora, Kenya, using high-resolution spatial analysis and FTIR spectrometry,” details the excavation strategy as well as much of the FTIR and spatial analysis of the site. It shows the clustering of archaeological and burned materials that suggests that this site may have evidence for fire use in the Early Pleistocene.

The second paper (in press), “Hominin fire use in the Okote Member at Koobi Fora, Kenya: new evidence for the old debate” details the work done to compare the materials found at FxJj20 AB to the experimental materials from Schick’s (1986) experimental work on site formation. This material begins to suggest that the site may indeed be in primary context.

The third paper (ready for submission), “Site formation and integrity of FxJj20 AB, Koobi Fora, Kenya and implications for fire in the Early Pleistocene archaeological record” details the orientation analyses of artifacts recorded with two total station data points on the long axis, as well as the micromorphological data about site formation. This study confirms that the site is in primary context and the determinations from the spatial analysis are valid reflections of conditions at the time of the site’s burial.

Chapter 2: Researching the nature of fire at 1.5 mya on the site of FxJj20 AB, Koobi Fora, Kenya using high-resolution spatial analysis and FTIR spectrometry

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Author list: ***Sarah Hlubik***[1]*, Francesco Berna*[2]*, Craig Feibel*[1]*, David Braun*[3]*, John W.K. Harris*[1]

1. Rutgers, The State University of New Jersey, New Brunswick, NJ

2. Simon Fraser University, Burnaby, BC, Canada

3. The George Washington University, Washington, DC

2.1 Introduction

Several studies show fairly convincingly that modern humans depend physically and biologically on the controlled use of fire (Carmody and Wrangham 2009; Wrangham and Carmody 2010; Wrangham and Conklin-Brittain 2003; Wrangham et al. 1999). However, the timing of the initial use of fire by hominins is contentious at best (James, 1989; Sandgathe et al., 2011; Sandgathe, 2017). Some scholars hypothesize that the dependence on fire use has deep roots in the *Homo* lineage (Wrangham, 2017). Morphological changes (larger body and brain, smaller teeth and gut) in *Homo erectus* beginning around 2.0 mya suggest that major changes in feeding strategies such as cooking or other food processing behaviors began at or before this time (Aiello and Wells 2002; Aiello and Wheeler 1995; Organ et al. 2011). While an increase in meat-eating (fat and protein) would have provided a greater number of valuable calories (e. g. Blumenschine and Pobiner 2007; Milton 1999; Speth 1989), without hunting to ensure continuous access to fresh meat resources, hominins would have been subject to toxins and pathogens that develop in spoiling meat (Ragir et al., 2000; Smith et al., 2015). Using fire to cook meat and vegetal foods would have reduced their potential toxicity and, most importantly, increased the caloric return of these foods. This would reduce the amount of metabolic energy needed for digestion by diminishing chewing time and by breaking down complex starches and proteins into more efficiently digestible compounds (Carmody and Wrangham 2009; Wrangham and Conklin-Brittain 2003; Wrangham et al. 1999). Evidence for acquisition of meat resources dates to at least 2.6 mya (Semaw et al., 2003), and potentially as early as 3.4 mya (McPherron et al. 2010), while persistent carnivory is shown in the record beginning about 2.0 mya (Ferraro et al., 2013). The gap between including some meat in the diet and persistent carnivory indicates that some barrier existed to the incorporation of meat in the hominin diet prior to 2 mya. It is possible that the acquisition of the use of fire in the behavioral repertoire of hominins was responsible for this. To test this hypothesis, we must establish whether the use of fire, in some capacity, is present in the Early Pleistocene archaeological record associated with *H. erectus* or *H. habilis*.

This paper aims to illustrate the nature of the 1.5 mya old evidence for fire at the site of FxJj20 AB, located in Koobi Fora, Kenya. The study includes high-resolution mapping and spatial analysis, soil micromorphology and Fourier transform infrared spectroscopy (FTIR) characterization of the archaeological record. We carefully examine the nature of fire evidence, and its distribution and relation to hominin activities, to determine whether there is a statistically significant association between the spatial distribution of fire evidence and evidence of other human activities (e.g. flintknapping or butchery). We recognize the difficulty of claiming that ancient hominins controlled fire at 1.5 mya in the absence of numerous sites with similar patterns. Nevertheless, the work presented here represents a fundamental data point and, more importantly, a methodological benchmark for the investigation of the nature of fire evidence in Early Pleistocene open-air sites of Africa and Eurasia.

2.2 Background

Archaeological research in Europe and Southwestern Asia shows that control and maintenance of fire begins sometime in the middle to late Middle Paleolithic (Roebroeks and Villa 2011; Shimelmitz et al. 2014; Sorensen, Roebroeks, and van Gijn 2014). Qesem Cave, Israel, contains evidence of habitual use of fire (Sandgathe, 2017) and hearth-like features associated with an Achuelo-Yabrudian industry at 300ka (Karkanas et al., 2007; Shahack-Gross et al., 2014; Shimelmitz et al., 2014; Barkai et al., 2017). True hearth features appear in the latter half of the Middle Pleistocene with the appearance of Neanderthals (James, 1989), while sites like Campitello, Italy, (MIS 6: Mazza et al. 2006) have evidence for materials like mastics that are not possible to produce without fire. However, some evidence for potential use of fire at archaeological sites from the Early and Middle Pleistocene throughout the Old World extends much further back in time (Clark and Kurashina, 1979; Gowlett et al., 1981; Clark and Harris, 1985; Alperson-Afil and Goren-Inbar, 2006, 2010; Preece et al., 2006; Berna et al., 2012; Goldberg et al., 2017) (See Table 1). At many of these sites, however, the anthropogenic nature of the fire is called into question because of the contexts in which the residues are found (Isaac 1982; Roebroeks and Villa 2011; Stahlschmidt et al. 2015). At Swartkrans, South Africa (1.0-1.5 mya), fire residues are found in deposits filling karstic sinkholes (Brain, 1993; Gibbon et al., 2014) while at Chesowanja, Kenya (~1.2 mya), they are found in alluvial settings (Gowlett et al., 1981); these are not ideal settings to investigate evidence of controlled fire.

Table 1: List of sites prior to 400 kya with evidence of fire.

Africa		
Koobi Fora, FxJj20, Kenya [a]	1.5-1.6 mya	Burned lithics, reddened sediment
Chesowanja, GnJi1/6E, Kenya [a,b]	1.42 mya	Reddened sediment
Gadeb, Ethiopia [a]	0.7-1.5 mya	Burned lithics
Swartkrans, South Africa [c,d]	1.0 mya	Burned bones
Wonderwerk, South Africa [e]	1.0 mya	Ash, charcoal, burned bone
Southwest Asia		
Gesher Benot Ya'aqov, Israel [f]	780 kya	Burned lithics, charcoal, burned seeds
Qesem Cave, Israel [g]	400-200 kya	Hearths, ash, burned bone
Tabun, Israel [h]	350 kya	Hearth, ash, phytoliths
Hayonim, Israel [i]	250-100 kya	Ash, charcoal, phytoliths
Europe		
Atapuerca, Spain [j]	1.2-.780 mya	Dispersed charcoal
Isernia, Italy [j]	606 kya	Burned bone, burned sediment
Boxgrove, England [j]	MIS 13	Charcoal
Highlodge, England [j]	MIS 13	Charcoal
Beeches Pit, England [j, k]	MIS 11	Burned lithics, burned bone, burned sediment, hearth
Verteszöllös, Hungary [j]	MIS 9-11	Burned bone, hearth
Biltzingleben, Germany [j]	MIS 9-11	Charcoal, burned lithics, burned bone
Terra Amata, France [j]	380-239 kya	Charcoal, burned lithics, burned bone, hearth
Orgnac, France [j]	MIS 9-8	Burned bone, ash
Petit Bost, France [j]	MIS 9/8	burned lithics

List of sites prior to 400 kya with evidence of fire. References: a: Clark and Harris 1985; b: Gowlett et al. 1981; c: Brain 1993; d:Gibbon et al. 2014; e: Berna et al. 2012; f:Alperson-Afil and Goren-Inbar 2010; g: Shahack-Gross et al. 2014; h: Albert et al. 1999; i:Shahack-Gross, Bar-Yosef, and Weiner 1997; j:Roebroeks and Villa 2011;k: Preece et al. 2006

The Atapuerca sites, in northern Spain, contain dispersed charcoal throughout their sequences, which cannot be considered evidence for control of fire on a site (Wil Roebroeks and Villa, 2011). To determine whether fire was used by ancient hominins, fire evidence needs to be found in minimally disturbed anthropogenic contexts with a demonstrable association with hominin activities (Berna et al. 2012).

Researchers at Gesher Benot Ya’aqov (GBY) found a number of burned microartifacts (artifacts less than 2cm in maximum dimension) clustered together, while macroartifacts (artifacts greater than 2cm in maximum dimension) were found mostly unburned and away from the burned microartifacts (Goren-Inbar et al., 2004; Alperson-Afil and Goren-Inbar, 2010; Alperson-Afil, 2017). The researchers proposed that this pattern mirrored the toss and drop zones proposed by Binford (1983). Macroscopic components of the purported hearths at GBY no longer remained intact, but the pattern of burned and unburned artifacts was preserved and used to pinpoint their original locations (Alperson-Afil, Richter, and Goren-Inbar 2007). The site provides strongly suggestive evidence for the controlled use of fire at 780ky, even in absence of commonly used proxies such as microscopic wood ash and/or burnt sediment.

Wonderwerk Cave contains evidence of fire in Acheulean contexts dating back to ca. 1 mya (Berna et al. 2012). Micromorphological investigation showed the presence of cm-thick intact paleosurfaces containing calcified and ashed plant remains (Berna et al., 2012; Goldberg et al., 2015; Thibodeau, 2016). The microscopic evidence, combined with evidence of bone burned at temperatures above 400^{o}C and ironstone manuports with characteristic potlid fractures (resulting from the exposure to high heat) suggests that hominins using Wonderwerk cave were using fire in some capacity (Berna et al. 2012).

The Koobi Fora FxJj20 site complex spurred the debate over fire use by early hominins soon after the original excavations of all three sites in 1972 and 1973. The sites FxJj20 East and FxJj20 Main were subsequently excavated in the 1970s and into the 1980s as more finds were discovered (Harris 1997). During excavations at FxJj20 East and FxJj20 Main, discrete concentrations of rubefied sediment aggregates were found throughout the site (Bellomo and Kean 1997; Harris 1978, 1997). It was proposed that these concentrations were the remains of ancient fires and subsequent analysis using magnetometry, thermoluminescence (TL) (Bellomo 1994; Bellomo and Kean 1997), and phytoliths (Rowlett, 2000) indicated that these may indeed be related to fire. Spatial analysis of the materials recovered during the excavation (Bellomo 1994) indicated that stone tool and bone concentrations were closely associated with the rubefied sediment concentrations, further indicating that these patches may be the result of fire associated with hominin activities.

Earlier excavations at the FxJj20 sites did not have the advantage of modern technology to aid in mapping and were not undertaken with a methodology focused on the recovery of small finds. Artifacts and bone were plotted by hand and smaller (< 2cm in maximum dimension) artifacts and bone were recovered in the screen. While items recovered in the screen are useful for many analyses, such as lithic technology and faunal lists, these materials are less suitable for high-resolution spatial analysis as imprecise placement can skew analyses.

Since the original excavations at the FxJj20 sites, advancements in recovery and analysis techniques have enhanced the ability to identify hominin fire use (Berna and Goldberg 2007; Goldberg and Berna 2010; McPherron and Dibble 2002). Recovery of all possible artifacts, piece-plotted with the aid of a total station, make it possible to map even the smallest artifacts, ecofacts, samples, and feature boundaries with millimeter accuracy (McPherron and Dibble 2002). Soil micromorphological techniques, coupled with FTIR microscopy, allow for the identification of microscopic fire evidence such as wood ash, burnt bone, burnt soil or micro-charcoal (Berna et al. 2012; Berna and Goldberg 2007; Goldberg and Berna 2010). The use of portable FTIR allows for the identification of burned materials in the field or lab (Berna and Goldberg 2007; Weiner 2010). Spatial analysis using advanced geographical information systems (GIS) enable the identification and visualization of density related patterns (Anselin and Getis 1992; Henry 2011).

Fire itself is relatively easy to detect in the archaeological record using methods such as soil micromorphology, FTIR, magnetic susceptibility, paleomagnetism and thermoluminescence (Shahack-Gross et al., 1997; Berna and Goldberg, 2007; Goldberg et al., 2017). Wild fire evidence is described as diffuse and irregular (Gowlett et al., 2017) and recent paleoenviromental studies show that, with expansion of grasslands, the East Africa landscapes became progressively fire-prone at the beginning of the Pleistocene (Magill et al., 2013), so the probability that wildfire affected the remains of prehistoric camps is higher in East Africa than in other geographic regions. Conversely, anthropogenic fire at base camps or in living spaces in the Early Pleistocene should be distinguishable as fairly localized evidence of fire closely associated with artifacts. Thus, to be able to distinguish between wildfire and human made fire it is fundamental to produce high resolution maps of heated and not heated macro- and microscopic artifacts and ecofacts. Evidence of exotic fuel brought to the site and/or fire starting techniques (e.g., pyrite, marcasite, tinder fragments) can be used to assess the anthropogenic origin of fire, especially if found in close association with evidence of human activities such as stone tools or butchered animal bone. All individual pieces of evidence need to be evaluated within the larger context of the site itself and in reference to other evidence found.

2.3 Materials and Methods

2.3.1 FxJj20 AB Site

All three FxJj20 sites are located on weakly lithified, fine-grained, floodplain tuffaceous silts (Harris 1997). The site of FxJj20 AB, discovered in 1973, is located about 150 m northeast of the FxJj20 East and FxJj20 Main sites (Figure 1). The artifacts and bone appear to be deposited on a gentle (~5^{o}), east to west slope. A small 16 m^2 test-excavation was undertaken, and excavator notes describe recovering reddened clasts in the screen, though none were recorded *in situ.* The 1970s excavation resulted in a collection of lithics (n = 2626) which are clearly the result of intentional flaking, often showing flake scars, but preserving no bulbs of percussion or platforms (Harris 1997).

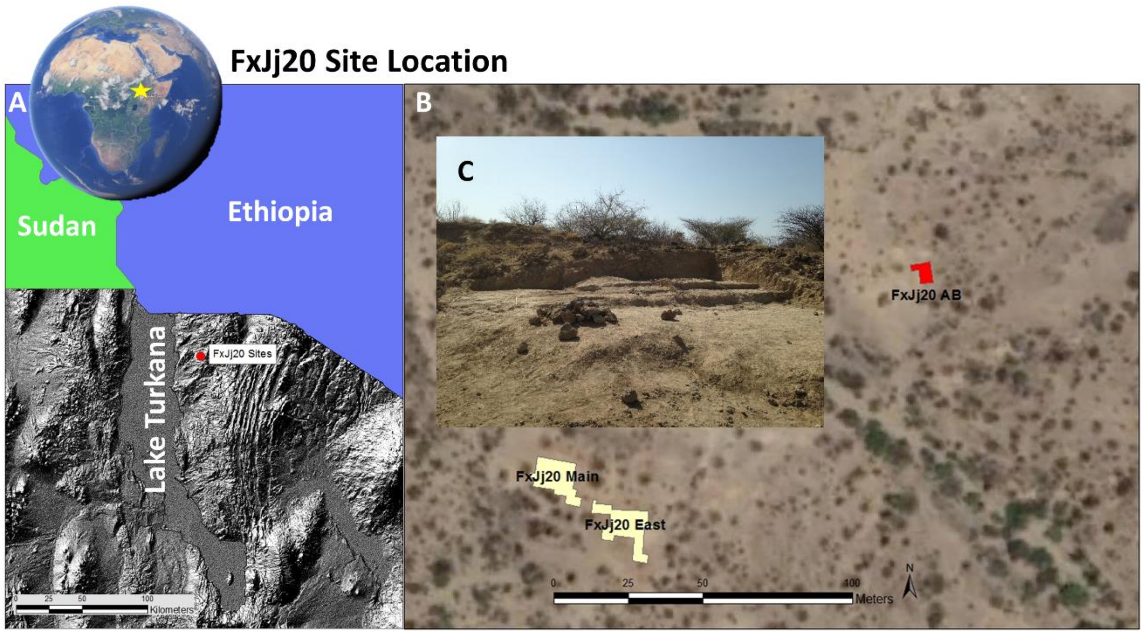

Figure 1: : (a) General location of the FxJJ20 Site complex, located on the Karari Ridge, in Koobi Fora, Northern Kenya; (b) Location of the FxJj20 Sites in relation to each other. FxJj20 AB is located approximately 150m to the north and east of the FxJj20 East and Fxjj20 Main Sites; image from GoogleEarth. (c) Photo of the excavation of FxJj20AB facing southwest across the site

In 2010, we resumed excavations at FxJj20 AB and expanded the site by 24 m^2 to the east and north of the original excavation. We hoped to detect discrete, consolidated concentrations of reddened sediment, similar to those found at FxJj20 East and FxJj20 Main (Harris 1973). Such concentrations were not found, but a preliminary spatial analysis of the artifacts found at the site identified 'Locus 1', a circular, low-density area surrounded by a higher-density concentration in the northeast portion of the site (Figure 2). The artifacts making up a large concentration around Locus 1 are primarily smaller than 2 cm in maximum dimension (henceforth 'microartifacts'), while a larger concentration of larger artifacts (>2cm in maximum dimension) were recovered further to the west of the largest concentration of microartifacts. As all the surrounding squares had been excavated to the same elevation as the square containing Locus 1, and small artifacts as well as bone fragments surrounded Locus 1, we hypothesized that Locus 1 might be the location of a fire feature. On this assumption, we have continued excavation and sampling of the site to resolve this question.

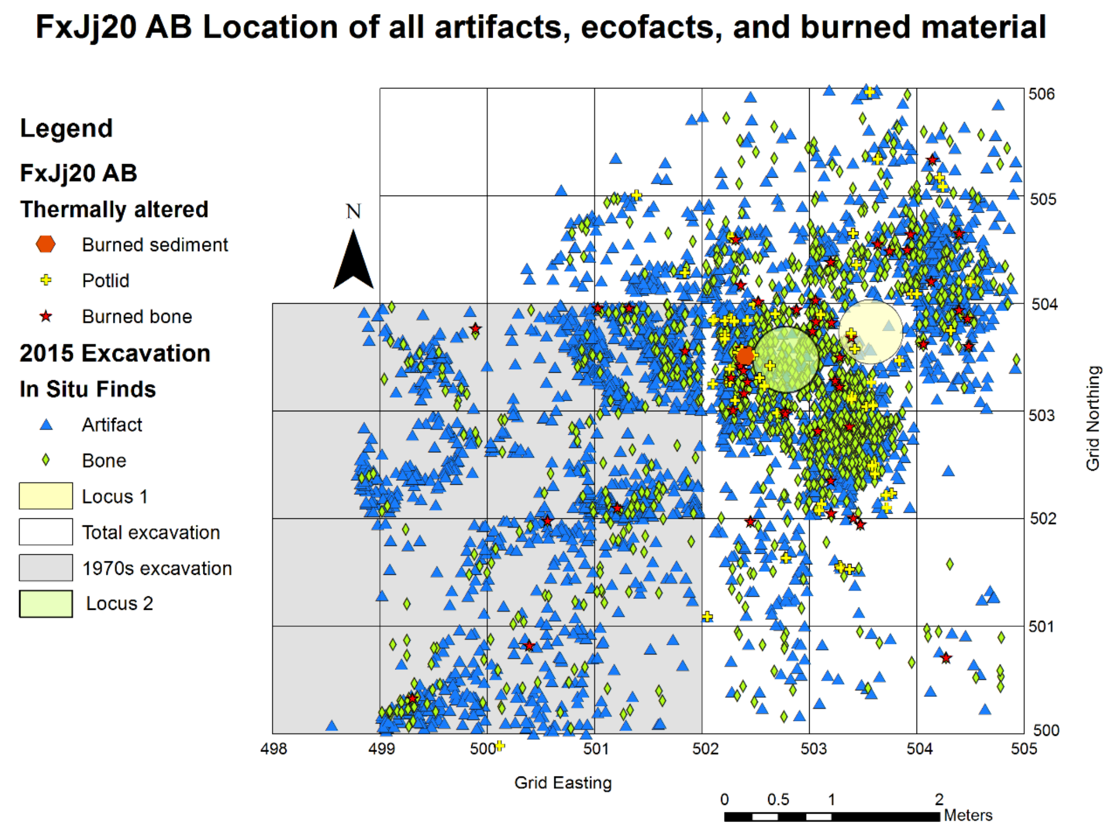

Figure 2: Location of all artifacts and ecofacts found on FxJj20 AB. Locus 1 is highlighted in tan; original 16^2 m 1973 excavation is highlighted in cream. Potlids are pieces of stone debitage identified through lithic analysis as being consistent with experimentally-derived potlids; Burned bone and burned sediment are identified through FTIR analysis. Locations of all materials from the new excavations are obtained through Total Station, while materials from original excavation were plotted by hand.

2.3.2 Excavation Methods at FxJj20 AB Site

Between 2010 and 2015, 24 squares were excavated to the depth of the artifact-bearing layers, nine of which were further excavated to sterile layers; one was left unexcavated to serve as a stratigraphic reference and allow for micromorphology sample collection to document any microscopic stratigraphic features.

The excavation of FxJj20 AB is designed to document the three-dimensional locational data of as many artifacts as possible, particularly microartifacts. Dental tools and paintbrushes are the primary excavation tools; sediments are removed in 5-cm levels. Spatial data is recovered using a total station and handheld data collector running EDM Mobile (McPherron and Dibble 2011). Obviously elongated artifacts are shot in using two shots on the long axis to determine artifact orientation and help understand site formation processes (McPherron 2005). Sediment is screened through a 2 mm mesh screen, to ensure recovery of small artifacts and ecofacts. Recovered materials are classified and recorded (see SOM for details). With this methodology we collect three-dimensional coordinates for ~95% of the recovered material allowing high-resolution spatial analysis of the materials and enabling us to make predictions about activities on the site.

2.3.3 Soil Micromorphology

Soil micromorphology analysis was performed to characterize the sediments at the microscopic scale and reconstruct the history of local sedimentological processes. Several intact sediment blocks were collected throughout the site, following Stoops (2003) and Goldberg and Macphail (2006), to examine the entire stratigraphic sequence and features observable in the field. Intact sediment blocks were pedestalled *in situ* and wrapped with plaster of Paris strips. The top and north-south orientations were recorded on the blocks before removal. Labeled plastered blocks were cut out of the excavation, and re-wrapped them with more plaster of Paris and packing tape to ensure sample integrity during transportation and shipment to the lab. In the lab, blocks were air-dried at 50° C, embedded in styrene diluted polyester resin under vacuum, cured and cut into 2 x 3 inch and 1 x 2 inch blocks (chips). The chips were prepared into petrographic thin section slides by Spectrum Petrographics (Vancouver, WA). The thin section slides were analyzed by petrographic microscopy with an Olympus BX41 following the criteria in Stoops (2003) and by FTIR microscopy using a Thermo-Nicolet iN10 MX FTIR microscope (see below). The petrographic thin section slides were examined for composition and micromorphological features to identify remains of paleosurfaces, human activities and natural processes (i.e., bioturbation, and pedogenesis).

2.3.4 Heat Experiments

Over the course of several seasons (2012 through 2015), we conducted a number of heat experiments to build a reference collection of heated sediment, bone and local lithic raw materials. We investigated various lithologies including Gombe and Asille basalt. Gombe basalt comprises approximately 50% of the artifacts found at FxJj20 Main (Braun et al. 2009). These heat experiments were conducted in the lab and in the field to document visible heat-related changes (e.g., discoloration, fractures) and mineralogical transformations using FTIR (see below). Experimental work in the Geoarchaeology lab at Simon Fraser University (SFU) included firing sediment samples (taken from the center of FxJj20 AB), Gombe basalt, and Asille basalt in a muffle furnace (ThermoLyne 30400) at 400^{o} C, 550^{o} C, and 800^{o} C for four hours. Field experiments placed tested materials in camp fires fueled with wood locally available at Koobi Fora. Experimentally heated materials included cobbles and flakes of basalt, ignimbrite, chert, and chalcedony, all of which would have been locally available to hominins in the past. An infrared thermometer was used to measure the temperature of the experimental campfires; all fires reached temperatures above 550^{o} C and lasted at least 6 hours. We visually inspected heated raw materials in the field at Koobi Fora Base Camp, at the National Museums of Kenya in Nairobi (NMK), Kenya, and at the SFU lab. FTIR testing of unheated and heated materials was performed with a portable FTIR spectrometer (Thermo Nicolet iS5) at the NMK in Nairobi, and at the SFU geoarchaeology lab. Laboratory experiments of the basalts and subsequent FTIR testing are still ongoing, thus the results presented here are considered preliminary.

2.3.5 FTIR spectrometry and micro-spectrometry

FTIR spectrometry has been used extensively to characterize the organic and inorganic composition of archaeological materials, features and deposits (Weiner 2010), and in particular, identify heated materials in the archaeological record (Berna and Goldberg 2007; Berna et al. 2012; Shahack-Gross, et al., 1997; Shahack-Gross et al. 2014; Weiner 2010; Weiner et al. 2015). FTIR spectrometry makes it possible to recognize heat-induced mineralogical transformation in bone, chert, calcite and clay minerals (Berna 2010; Berna et al. 2007, 2012; Berna and Goldberg 2007; Shahack-Gross, et al. 1997, 2014; Weiner et al. 2015). Micro-destructive FTIR sampling (mg particles) was conducted on archaeologically collected bulk- and single-grain sediment samples, discolored aggregates, and bone and lithic fragments, as well as unheated and experimentally heated local sediment and lithic raw materials. Initial FTIR analysis was conducted at the NMK, Nairobi, Kenya, at the close of the 2015 field season. Further testing took place at the SFU lab. We ground samples with an agate mortar and pestle, mixed them with potassium bromide (KBr), and pressed them into pellets using a hand press (Pike Technologies). The pellets were analyzed using a Thermo-Nicolet iS5 spectrometer collecting 64 scans in the 4000 to 400cm^{-1} wavenumbers with a resolution of 4 cm^{-1} wavenumbers.

All materials (soil particles, bone fragments, lithic raw material flakes and pebbles) recovered from within Locus 1 (location of a potential combustion feature) were analyzed by FTIR to test for indications of heating. Materials from throughout the site were tested by FTIR spectrometry to look for other heated items and identify potential natural or anthropogenic combustion features. When burned material was identified, lithics and bone fragments collected from its proximity were also tested. Testing on random samples of bone and stone from throughout the site was also conducted.

A Thermo-Nicolet iN10 MX FTIR imaging microscope was used to analyze petrographic thin sections. Spectra of particles with diameter of 50 to 150 μm were collected in transmission and total reflectance modes with a Reflectocromat 15× objective between 4,000 cm^{-1} and 450 cm^{-1} at 8 cm^{-1} resolution.

2.3.6 Spatial analyses

Spatial analysis was performed using ArcGIS on stone artifacts, bone fragments and rubefied sediment aggregates recovered with three dimensional coordinates. Materials recovered in the screen (less than 5% of the material recovered during the 2010–2015 excavations) were excluded from the spatial analysis.

Vertical and horizontal spatial distribution of artifacts gives insight into the stratigraphic makeup of the site. Analysis of the vertical distribution of the artifacts, coupled with the soil micromorphological analysis, may shed light on whether the archaeological assemblage derived from a single occupation or a palimpsest of many occupations (Bailey 2007; Malinsky-Buller et al. 2011).

2.3.6.1 Spatial Analysis: Optimized Hot Spot Analysis (OHSA)

ArcGIS Optimized Hot Spot Analysis (OHSA) uses the Global Morans I statistic to calculate statistically significant clusters, or ‘hot spots’ within a specified geographical area. Unlike Kernel Density Estimates, which will run with any sample size, OHSA requires a minimum number of data points to work. When performed with the spatial analysis software ArcGIS

(ESRI), OHSA aggregates data within polygons. When no specific bounding polygon is identified, the analysis uses a predefined fishnet grid over the site and empty polygons are discarded from the analysis. If a bounding polygon is defined, empty polygons within the boundary are included in the analysis. The analysis corrects for a false discovery rate, by assuming that objects close to each other are likely similar, and lowering the p-value threshold for significance (e.g. 0.001 as opposed to 0.05). The analysis can be run with or without a weighting field. Weighting data can be any type of data upon which results are evaluated, such as population numbers in a city, or number of cases of disease. Without a weighting field, the analysis calculates spatial similarity alone. With a weighting field, the analysis calculates spatial similarity in relation to the weighted field.

For this analysis, OHSA were run with and without weighting. For all analyses, a 10 cm grid was overlaid on the site. For the weighted analysis, maximum dimension of artifacts was used. Densities of larger materials should be identified as ‘hot spots’, while densities of smaller materials will be identified as ‘cold spots’. This method obviates the need to classify materials as micro- or macro-artifacts and provides a more accurate method of grouping materials according to size. The analysis will show whether artifacts in a spatial cluster are similarly sized.

The OHSA will define areas on the site where there is significant clustering and also determine whether materials on the site cluster according to size. We expect that if material is clustering on the site, this will show up in the OHSA. If there are no clusters on the site, the analysis will return non-significant results.

2.3.6.2 Spatial Analysis: Toss and Drop Zones and Ring Distribution

Analyses of toss and drop zones, as proposed by Binford (1983), have taken several forms. They are used to identify the potential location of hearths where fire evidence such as ash and charcoal are absent (Vaquero and Pastó, 2001; Sergant et al., 2006; Alperson-Afil et al., 2007; Alperson-Afil, 2017), but they are also used to look at activities that may have occurred around known hearths (Henry 2012; Stappert 1989). While clusters of artifacts on a site can be useful to define the potential location of a combustion feature, this information should be corroborated by the presence of burned material. Potential toss and drop zones are identified by looking at the spatial distribution of bone and lithic materials on a site, coupled with an analysis of artifact size. As Binford (1983) directly noted around modern ethnographic campfires, smaller pieces of stone or bone (unintentionally produced waste) should be found in the drop zone, directly in front of the individual working with these items. Larger pieces (intentionally discarded waste) should be found in the toss zone, which can be expected to be found up to several meters distance behind, to the side, or in front of the individual (Binford 1983). Binford (1983) cites similar distributions patterns around hearths observed by John Yellen in the Kalahari and Richard Gould in Australia. A comparable pattern is observable in the distribution of burned archaeological materials at Gesher Benot Ya'aqov, (Goren-Inbar et al., 2004; Alperson-Afil and Goren-Inbar, 2006, 2010; Alperson-Afil et al., 2007; Alperson-Afil, 2017). If an activity area associated with fire is present, we expect small materials, or debitage, to be clustered together (i.e. drop zone), while larger materials will be found further out and clustered separately from small materials. We would expect large lithic tools, hammerstones, and flakes to cluster away from small debitage on the site.

Henry (2012), in a study of the Middle Paleolithic site of Tor Faraj, showed several potential configurations of the toss and drop zones which can be distinguished by the distribution of archaeologically recovered materials around a fire. Modeling his research after Stappert's (1989) work at Pincevent, Henry (2012) proposed that around 120 cm from the fire there would be a drop in numbers representing the "squat zone", the place where an individual would sit or squat to work around the fire. He developed three hearth-side ring profiles to describe the activities on a site. In his analysis, he looked at the frequencies of materials up to two meters from the center of the hearths found on the site (Henry 2012). He defined three observable patterns: Type I, Toss-zone dominant, where the majority of artifacts are found behind the individual working around the hearth; Type II, Drop-zone dominant, where some materials are found in the toss zone immediately behind the individual, but most are found in the drop zone in front of the individual; and Type III, Drop-zone dominant, where nearly all the material is found in front of the individual (Henry 2012). For Types I and II, Henry (2012) defines a 'squat zone' where the individual working around the fire would be sitting, and suggests that maintenance of the work area is responsible for these patterns. He suggests that the Type III pattern indicates that an individual did not move from his or her workspace and did not try to maintain a clear workspace (Henry 2012). These analyses do not take size into account, only frequency of artifacts from the center of the hearth. Comparisons between distributions from Tor Faraj, Jordan (Henry 2012), Pincevent, France (Stappert, 1989), and FxJj20 AB were made using a Kolmogorov-Smirnov test to determine whether the material from FxJj20 AB fits the patterns found at other Middle and Upper Paleolithic sites. If the profile of materials from FxJj20 AB match one of the ring profiles proposed by Henry (2012) we can hypothesize that it derived from behavior associated with a hearth.

2.4 Results

2.4.1 Excavation (Artifacts and Site formation)

The total number of artifacts recovered *in-situ* from all excavated areas at FxJj20 AB totals 2969 objects (Table 2). The distribution of recovered materials is given in Figure 2. The vertical spread of artifacts is between 8 cm in the lowest density areas to 20 cm in the highest density areas, with a maximum spread of 40 cm at the eastern edge of the excavation (Figure 3). The distribution of all materials recovered from the site shows a high density of artifacts spreading from the center to the northeastern portion of the site.

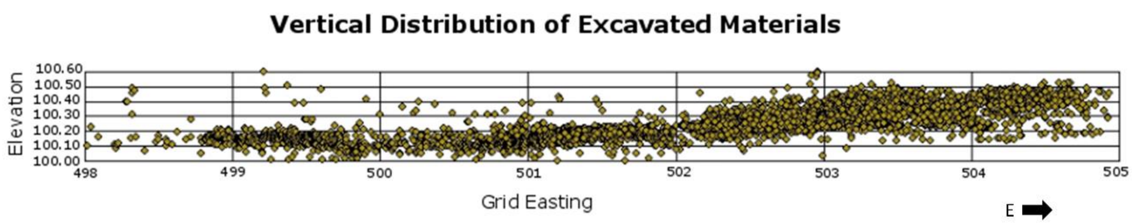

Figure 3: Vertical distribution of all materials on the site. Most materials cluster closely together, though there are a number of materials on the western end of the site that are found high in the spread. These materials may be related to a later occupation, but the low density suggests they may be part of the spread of the main concentration of materials.

A cross-section view of the excavation shows that the archaeological material is found on a slight (~ 5%) slope following the natural topography of the area (see Figure 3). Large and small finds are distributed throughout the excavation. There is no preferred orientation of the artifacts indicating no post-depositional transport of materials occurred (see Hlubik et al. forthcoming for details on orientation studies). Lithics from the excavation retain sharp edges and do not show any other signs transport and redeposition by water (Figure 4). Furthermore, there is a large proportion of small objects (40% have a maximum dimension less than 2cm) which would be affected by significant hydraulic action (Schick 1986). The numbers of artifacts found within each size class from the new (2010-2015) excavations at FxJj20 AB are consistent with those recorded by Schick (1986) from knapping experiments before winnowing treatments (Figure 5).

Table 2: List of all finds from the excavation at FxJj20 AB.

Excavated Materials	**Count**
Stone Tools	
Core	85
Cobbles	16
Flakes	1435
Whole flakes (n = 795)	
Broken flakes (n = 640)	
Flakes with potlid evidence (n = 3)	
Angular Fragments	1372
Debitage (n = 1328)	
Potlids (n = 4)	
Pebbles	52
Hammerstone	9
Total recovered artifacts	**2969**
Raw Material	
Basalt	2807
Quartz	19
Ignimbrite	60
Chert	58
Chalcedony	21
Feldspar	4
Total recovered artifacts	**2969**
Fauna	
Bone	1242
Tooth	102
Total recovered fauna	**1344**
Total recovered material	**4313**

Photographs of some artifacts from the FxJj20 Excavations

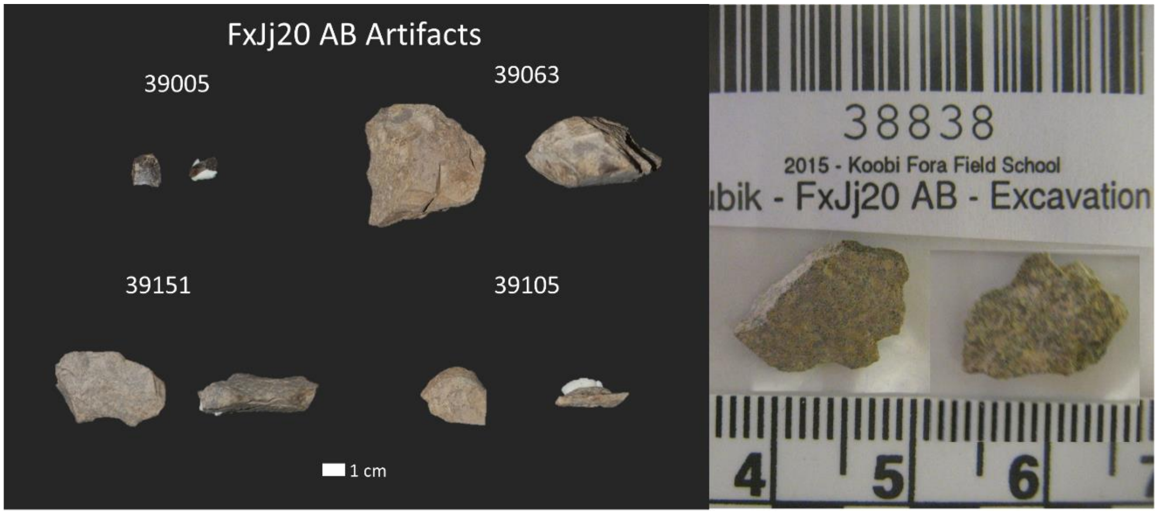

Figure 4: Left: Photographs of some artifacts from the FxJj20 Excavations. The artifacts are fresh, not rolled, and show no signs of being transported in by water. Right: Photograph of an example of a potlid identified through lithic analysis; ventral side (far right) is irregular with no signs of a bulb of percussion.

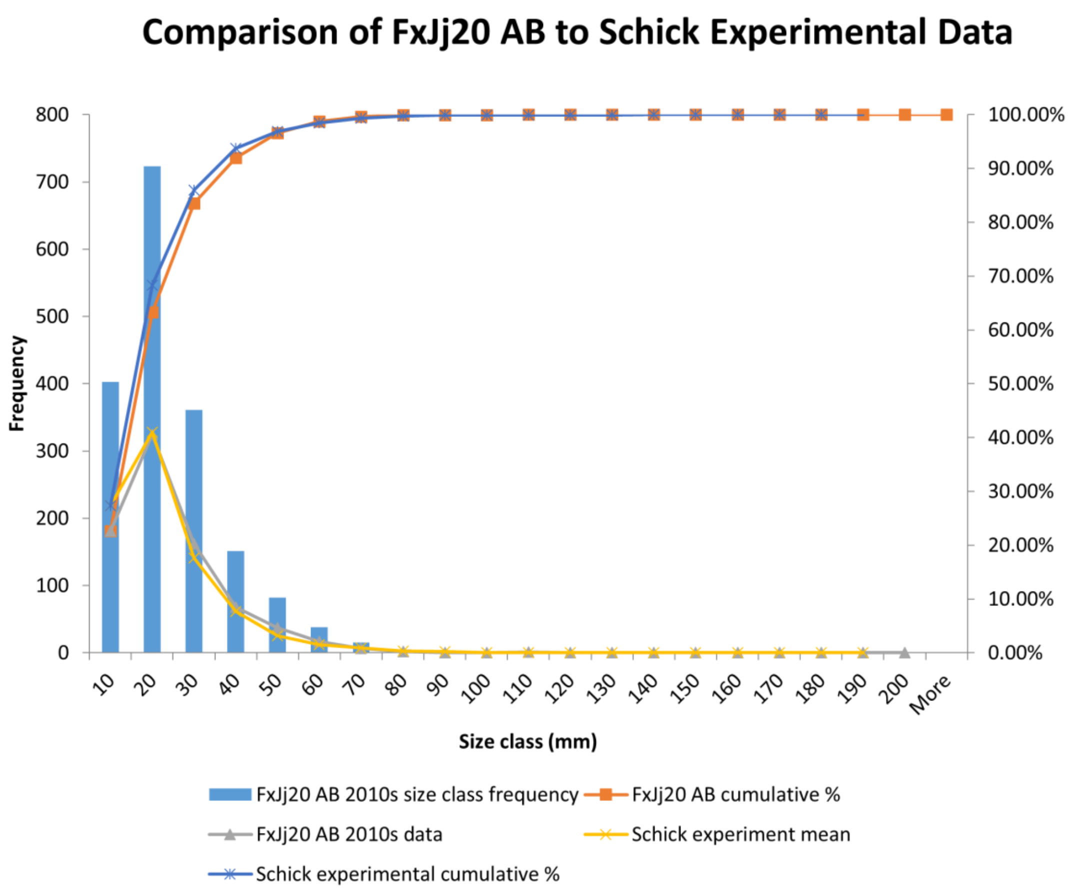

Figure 5: Comparison of FxJj20 AB 2010-2015 excavated artifact size profile to the experimental flintknapping data from Schick (1986) prior to any winnowing of experimental material. FxJj20 AB fits on the line with the Schick (1986) data. Comparison excludes data from 1970s excavations because excavation bias would have excluded the smallest materials.

While some identifiable pieces of bone were found during the 1970s-1980s excavation, most taxonomic identifications were made from tooth fragments which included representative species of the families Bovidae, Suidae, Equidae, Rhinocerotidae, Hippopotamidae, Cercopithecidae, Hystricidae, Chelonia, Aves, and Thryonomyidae (Harris 1997). Much of the faunal evidence found during the 2010-2015 excavations is extremely fragmentary and not identifiable beyond 'mammal', 'reptile', or 'fish' categories. Some are identifiable to general element (e.g. 'long bone'), but most are small fragments between 1 cm and 5 cm in maximum dimension and are identifiable only as "bone". Cortical surfaces are largely missing, making it difficult to determine whether butchery was occurring at the site. Faunal analysis is ongoing to determine the total portion of identifiable fauna, whether any fragments refit, and whether more specific elemental and taxonomic determinations can be made.

Aggregates of rubefied sediment are found throughout the site, with the highest concentrations in the central and southern portion of the site and much lower densities in the northern portions (Figure 6).

It is important to note that there are several low artifact density areas in the site, but one particular area (Locus 1) is located in the middle of several high-density clusters of objects. All squares adjacent to Locus 1 were excavated and had significant artifact densities. Approximately one quarter of Locus 1 (~0.7 m in diameter - see Figure 2) was excavated, and while some artifacts and bone were found, the density was much lower than the surrounding areas. However, a number of rubefied sediment aggregates (n=18) of were recorded but not collected from Locus 1.

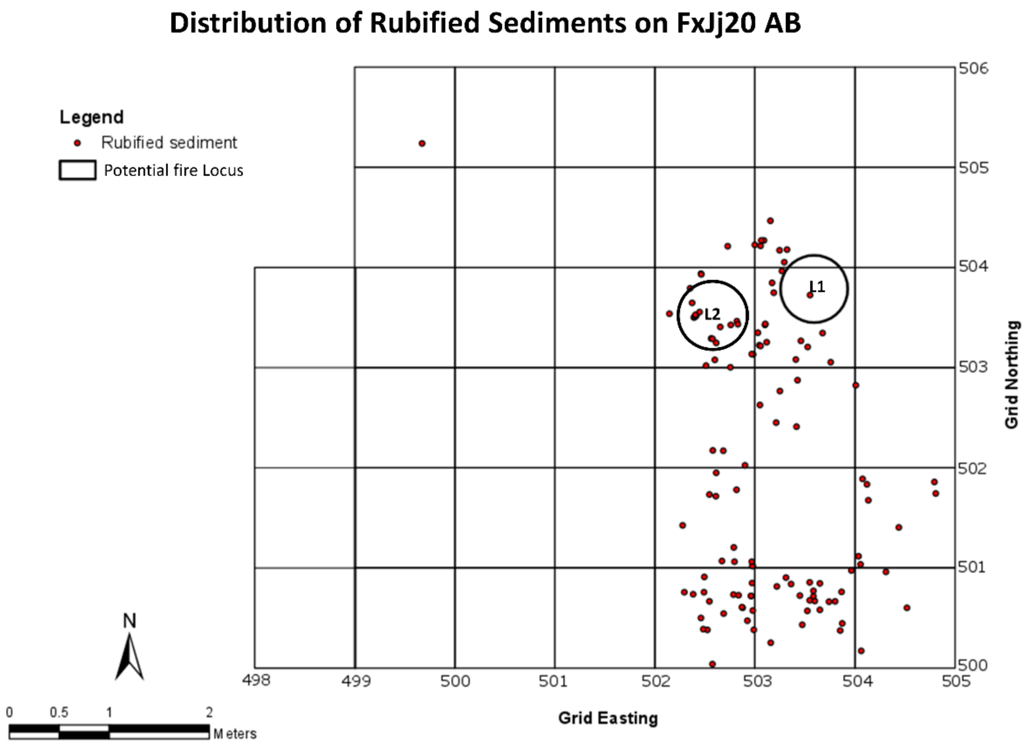

Figure 6: Distribution of rubefied sediments across FxJj20 AB. This map represents all rubefied sediment identified and shot in during excavation; only a fraction of the sediment was collected for further testing. The main concentration of rubefied sediments occurs in the southern portion of the site.

2.4.2 Soil Micromorphology

Micromorphological analysis of the excavated area shows that the sediment is locally composed of very weakly pedogenized tuff with feldspathic, micaceous and quartz silt to fine sand (Figure 7a). These sediment characteristics indicate that the archaeological material was deposited on a low energy, rapidly aggrading surface, such as should be expected on an active floodplain. The porosity of the sedimentary column consists of a few sub-cm size root channels and rare larger passage features and other fabric pedofeatures. Limpid laminated yellow clay coatings (Figure 7b) suggest post-depositional, low energy, subsurface translocation of clay formed from the weathering of the tuff. Interestingly, no calcium carbonate crystalitic b-fabric or pedofeatures have been observed in any of the thin sections analyzed. Evidence of soil mixing appears to be limited to grass roots, arthropods, and earthworm action. There is no evidence of major bioturbation from tree roots or by vertebrates like rodents or reptiles. It is likely, given the fine-grained nature of the sediments, the small size of the artifacts, and the lack of features produced by strong or prolonged pedogenesis, that the accumulation of sediment at the site was the result of seasonal or decadal flooding events from a nearby channel. The exact location of the channel has not yet been pinpointed (Harris 1997). Micromorphological analysis shows that the sediment of Locus 1 has the same general composition and structure of the adjacent areas. It differs slightly due to the presence of rare rubefied soil aggregates and a slightly higher content of fine sand (Figure 7c). No evidence of wood ash or bone fragments has been found in the blocks sampled so far from Locus 1 or other areas.

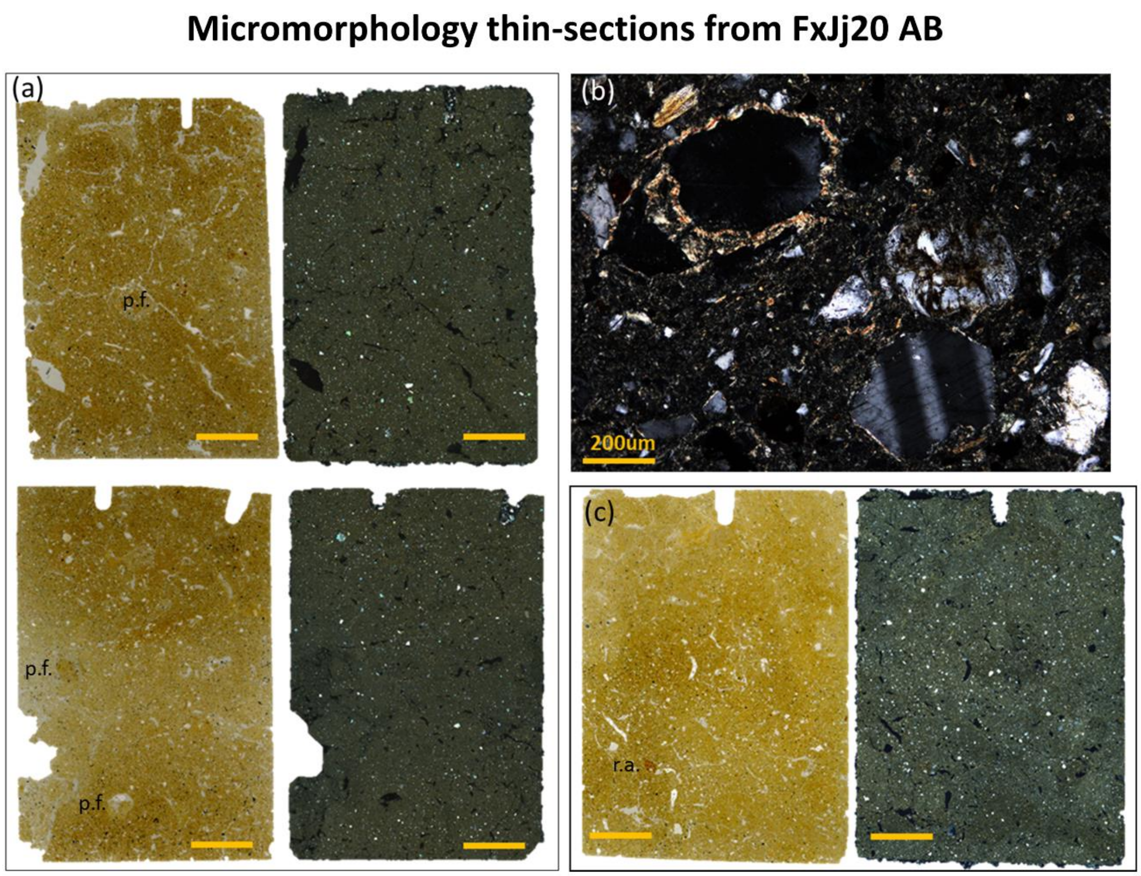

Figure 7: Soil micromorphology at FxJj 20AB. (a) Plane polarized light (left) and cross polarized light (right) scan of petrographic thin sections of intact block of local soil column, catalog number 25015 (scale bar = 1cm). Note the

silty clay loam texture, channel microstructure and a few passage features (p.f.). (b) Representative cross polarized light micrograph of the local ground mass (scale bar = 200 µm). Note the micaceous, feldspathic, and quartz composition of the poorly sorted silt and sand and the laminated clay coatings around pores and sand grains. (c) Plane polarized light (left) and cross polarized light (right) scan of petrographic thin sections of intact block from inside Locus 1 (scale bar = 1cm). Note sediment has similar composition and structure with respect to local sediment shown in figure 7(b) (sample catalog number 25015) and contains rare rubefied soil aggregates (r.a.).

2.4.3 Experimental work and archaeological evidence of burning

Upon being heated, Gombe and Asille basalt specimens did not exhibit a color change, but large pieces exposed directly to fire often spalled in convex sub-rounded flakes (a.k.a., potlids), sometimes reducing an entire cobble through the process and producing thousands of rock fragments. These potlids lack striking platforms or bulbs of percussion (Figure 4) and are distinguishable from flakes produced by knapping activities. During the firing experiments, the potlids projected out of the fire, sometimes to a distance of several meters. Experimental potlids generally have an irregular surface texture that contrasts with the smoother texture observed on debitage flakes derived from stone knapping. Smaller flaked pieces of basalt sometimes sustained potlid fractures, but more often emerged from the fire unchanged. Forty-four archaeological specimens of basalt were identified as potlids through comparison with experimentally produced potlids and debitage. The 44 archaeological potlids are found scattered throughout the site and are plotted in Figure 2. This kind of spatial distribution is expected since potlids can be ejected several meters from the fire. The incidence of numerous potlids on the site indicates the presence of fire, but it is not expected to indicate the exact location of the fire.

One piece of reddened chert was found roughly 3 cm to the southeast of the edge of Locus 1. The chert from FxJj20 AB is generally a yellow-brown color. This reddened chert retained some of the original brown color along one edge, but over 90% of the piece is a deep red color. The reddening of the piece is similar to the heat-induced discoloration observed in other chert samples (which had similar coloration prior to heating) and thus is considered to be burnt (Purdy and Brooks, 1971).

Unheated and heated samples of the two principal local raw materials, Gombe and Asille basalts, were analyzed by FTIR. Gombe and Asille basalts have over all similar FTIR spectra. Gombe basalt shows a unique hydroxyl absorption at ca. 3620 cm^{-1}, assigned to weathered olivine. Upon heating Gombe basalt to 500^{o} C the FTIR absorption at 3620 cm^{-1} is lost (Figure S4). Although it would be possible to use FTIR to distinguish between unheated and heated Gombe Basalt, unfortunately the FTIR patterns of unheated and heated Asille basalts and heated Gombe basalt are statistically undistinguishable (Figure 8). Thus, we do not consider FTIR alone to be a reliable method for unequivocally distinguishing between burned and unburned Gombe and Asille basalts.

FTIR curves of heated and unheated Gombe and Asille basalts

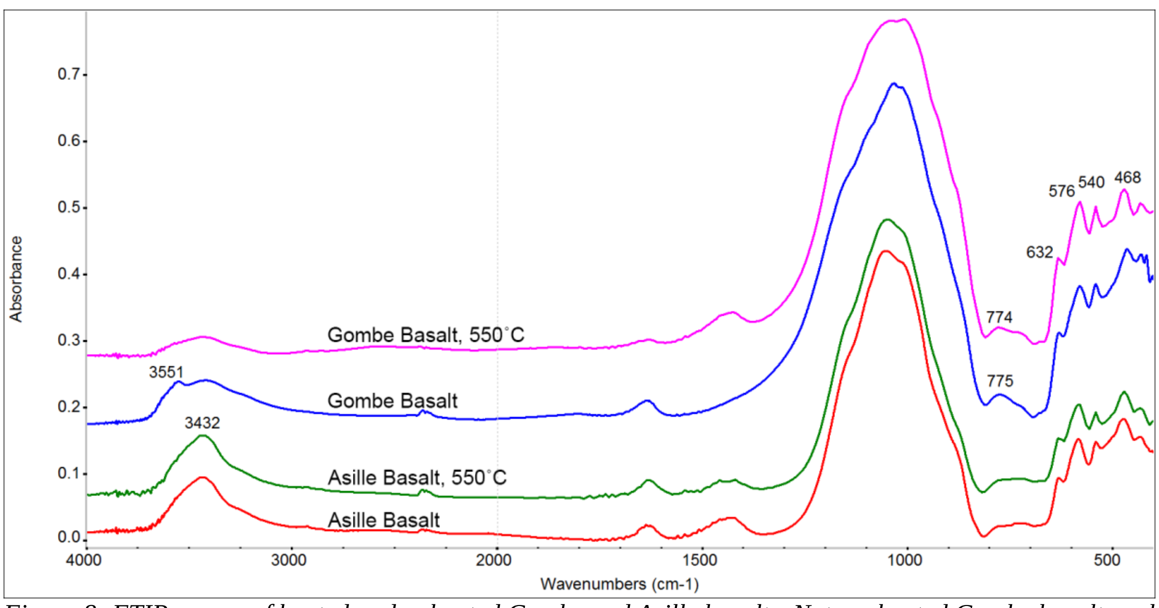

Figure 8: FTIR curves of heated and unheated Gombe and Asille basalts. Note unheated Gombe basalt peak at 3551 disappears with heating, making the curve similar to the heated and unheated Asille basalts. No significant differences exist between the FTIR spectra of heated and unheated Asille basalts.

Experimental lab work showed that when sediment from the site was heated, it underwent a dramatic color change from a light greyish tan to a deep red color (Figure 9b). This color change was incremental according to temperature, with the material burned at 400° C turning only slightly red and the material burned at 800° C turning a deep red. FTIR analysis also shows clear spectral differences between the unburned and burned sediments, with temperature-dependent pattern characteristics (Figure 9b).

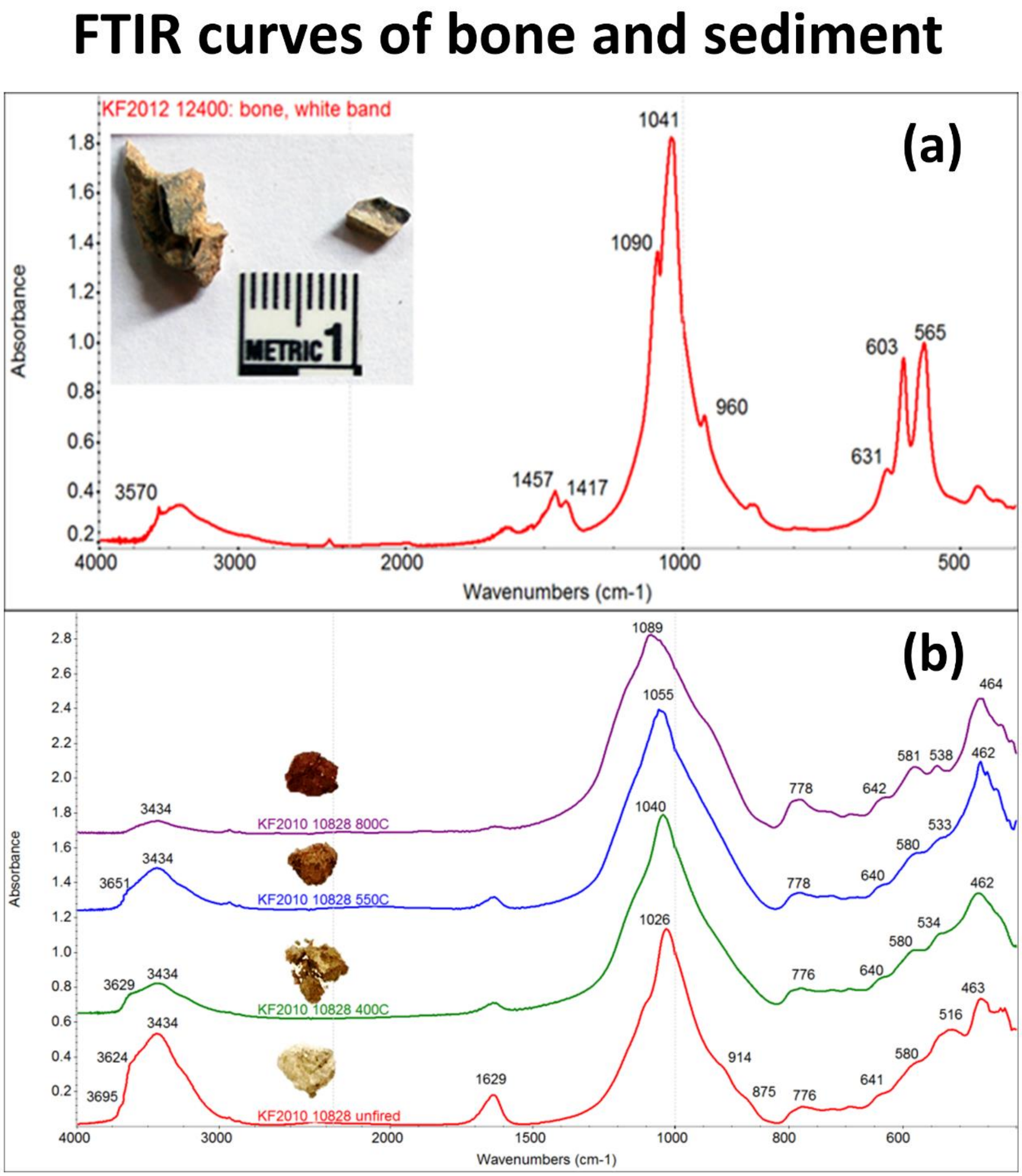

Figure 9: (A) FTIR spectrum of bone sample 12400 showing absorption at ca 565, 603, 630, 960,1040, 1090, 1415, 1455, and 3570 cm^{-1} characteristic of bone carbonate hydroxyapatite heated to ca 550 ˚C (Berna, 2010). (B) FTIR spectra of unheated (red pattern) and experimentally heated FxJj20AB sediment to 400 ˚C, 550 ˚ C and 800 ˚ C. Note the weak absorptions at 915, 3625, and 3695 cm^{-1} of kaolinite in the unheated sediment that disappear upon

heating the sample to 400 ˚ C. Also, note the shift of the major Si-O band from 1026 to 1089 cm^{-1} upon the incremental heating of the sediment.

Over 600 pieces of bone, 170 pieces of rock, and 24 samples of discolored sediment were tested using FTIR. Of these, 50 pieces of bone, and five samples (one *in situ)* of rubefied sediment were found to show evidence of being heated. Of the materials found within Locus 1, one bone fragment had FTIR absorptions characteristic of being burned above 500° C and below 700° C (Berna 2010) (Figure 9a). One sample of rubefied sediment, found approximately 1 m East of Locus 1, was identified using FTIR as being burned. Around this, six pieces of bone were identified as burned (Figure 2). An additional 43 bone specimens from other areas of the site were identified as burned.

2.4.4 Spatial analysis

Spatial analysis shows distinctive clusters of material on the site, both horizontally and vertically. The results of individual analyses are discussed below.

2.4.4.1 Spatial analysis: Optimized Hot Spot Analysis (OHSA)

Horizontally, the artifacts occur in one large dominant cluster in the northeastern portion of the site (Figure 10) with several smaller clusters to the southeast. The OHSA identified the large cluster as significantly different from a random distribution at a 99% confidence level (Figure 10). Overall, the clusters are composed of similarly sized materials (Figure 11). Significant clusters of artifacts larger than 2 cm are shown in red, while significant clusters of artifacts smaller than 2 cm are shown in blue. Areas with no distinctive clustering of certain size class specimens are indicated with cream-colored circles – these clusters contain materials that fit into both large and small categories.

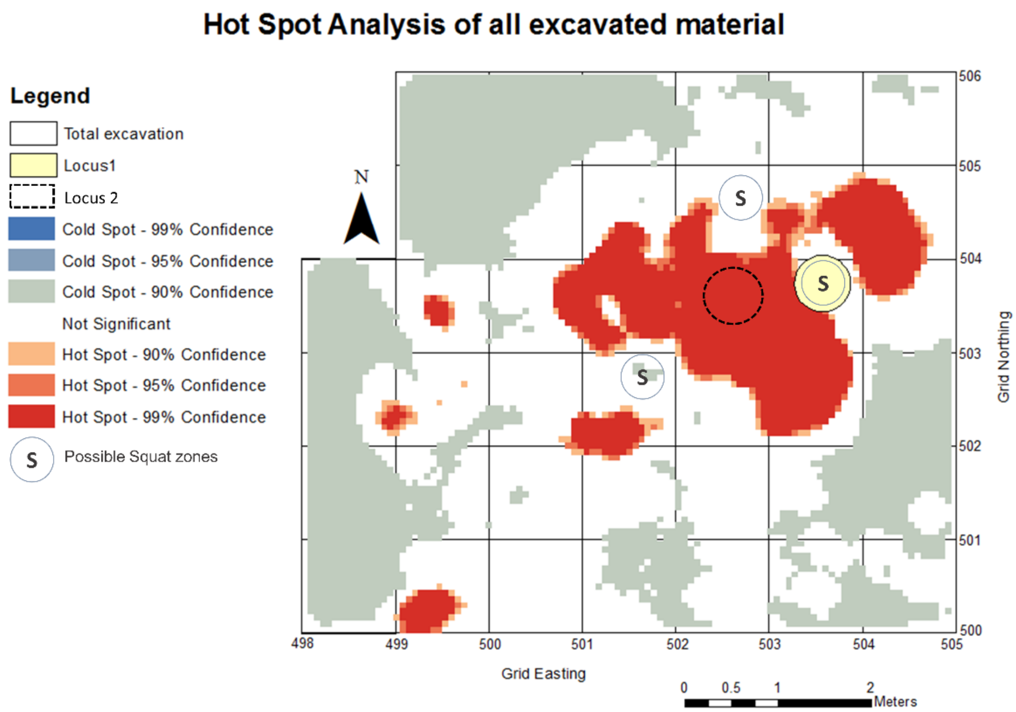

Figure 10: Hot-spot analysis showing areas where density of materials is statistically different from random. High-density areas are denoted in red, low-density is in blue and statistically insignificant results have no color. Potential squat zones are places on the site where knappers could have been positioned. They are noted here with and "S" in a circle.

Specimens of bone tend to be found in clusters that overlap with the concentrations of stone material, particularly the smaller artifacts (Figure 11). Clustering of artifact and bone are highest around Locus 1: smaller artifacts cluster primarily to the west and southwest, bone clusters primarily to the south and west as well, but wraps around to the north, and larger artifacts cluster to the west of Locus 1. The small cluster of materials to the northeast of Locus 1 is comprised primarily of artifacts, which are both large and small.

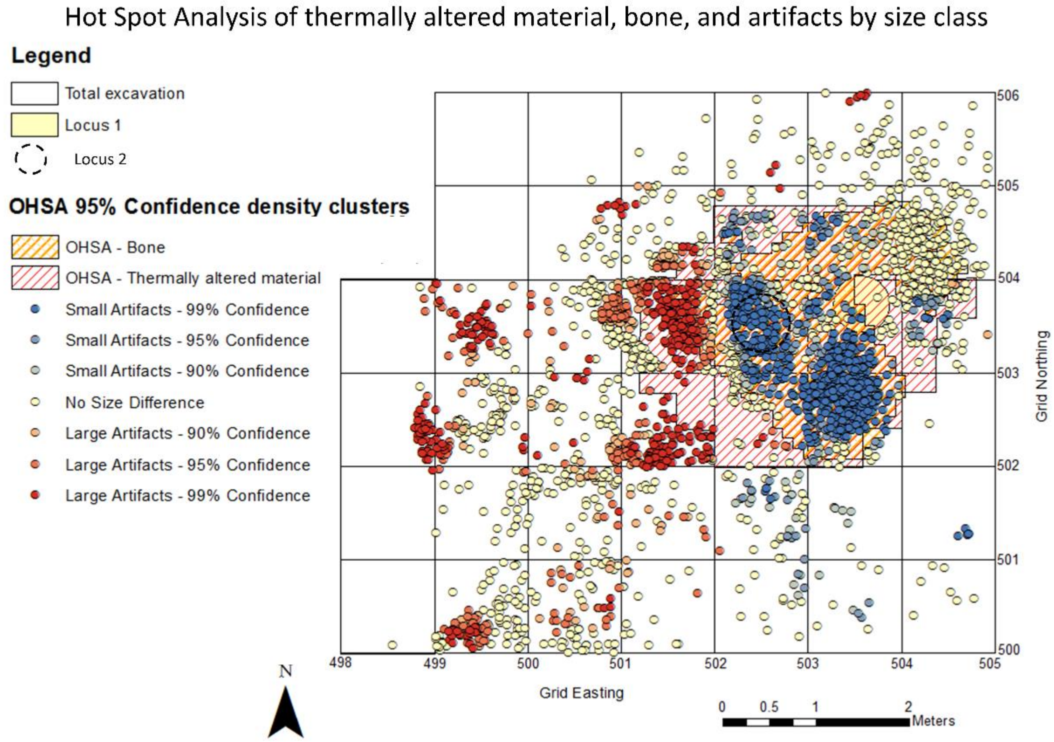

Figure 11: Hot Spot Analyses of bone, thermally altered materials, and artifacts by size. Smaller artifacts, bone and burned materials cluster together to the southwest of Locus 1, in and around Locus 2. Larger artifacts cluster further to the west of Locus 1 and Locus 2.

One aggregate of rubefied sediment was recovered within Locus 1 and more are found dispersed throughout the central and southern portions of the excavation site. A small group of burned materials (potlids, bone, sediment aggregates) is found to the west of Locus 1, and constitutes a statistically significant cluster of burned materials, which could be thus considered the location of a contained fire.

2.4.4.2 Spatial analysis: Toss and Drop Zones and Ring Distributions

The spatial distribution around Locus 1 is compatible to that of combustion features identified using the toss and drop zones analysis (Binford 1980, 1983). Specifically, smaller materials are found close to Locus 1, along with high concentrations of bone, while larger materials are found more distant from Locus 1. Histograms showing the distribution of artifacts throughout the entire site (Figure 12) show the highest concentrations of artifacts are adjacent to Locus 1. The ring distribution of the materials from around Locus 1 shows that the greatest numbers of materials are found between 80 and 120 cm from the center of Locus 1 (Figures 13c and 14b). Type III hearths are not maintained in the same way as Type I and II hearths, but the ground immediately around the knapper is likely to have a lower density than the surrounding area. Potential squat zones for FxJj20 AB are labeled on Figure 10.

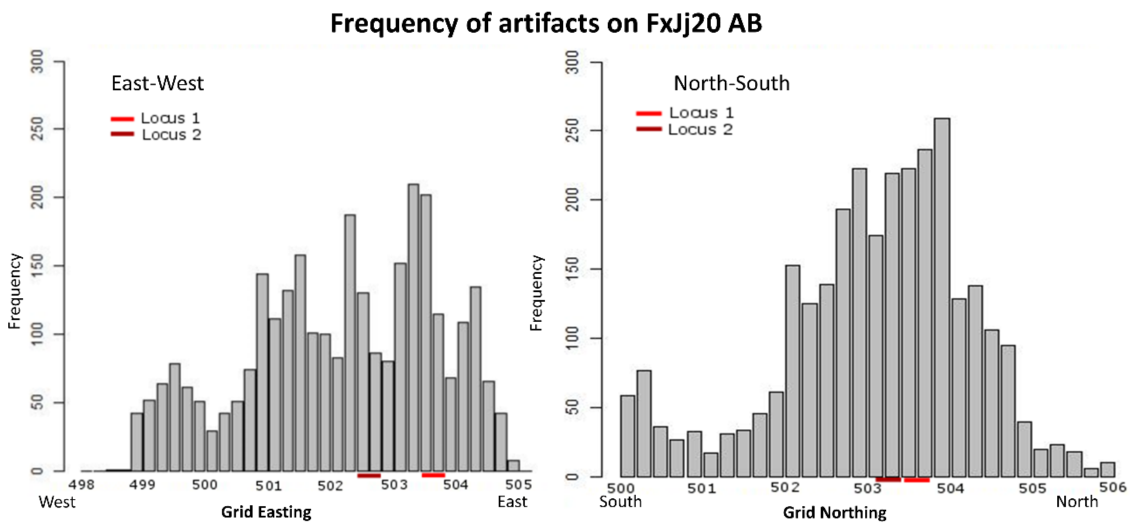

Figure 12: Histograms showing the distribution of artifacts east to west (left) and north to south (right) through the site. Red and maroon bars indicate the location of Locus 1 (red) and Locus 2 (center of burned cluster; maroon). Highest numbers of artifacts are found around both loci; there is a peak in artifact number west of both Locus 1 and Locus 2.

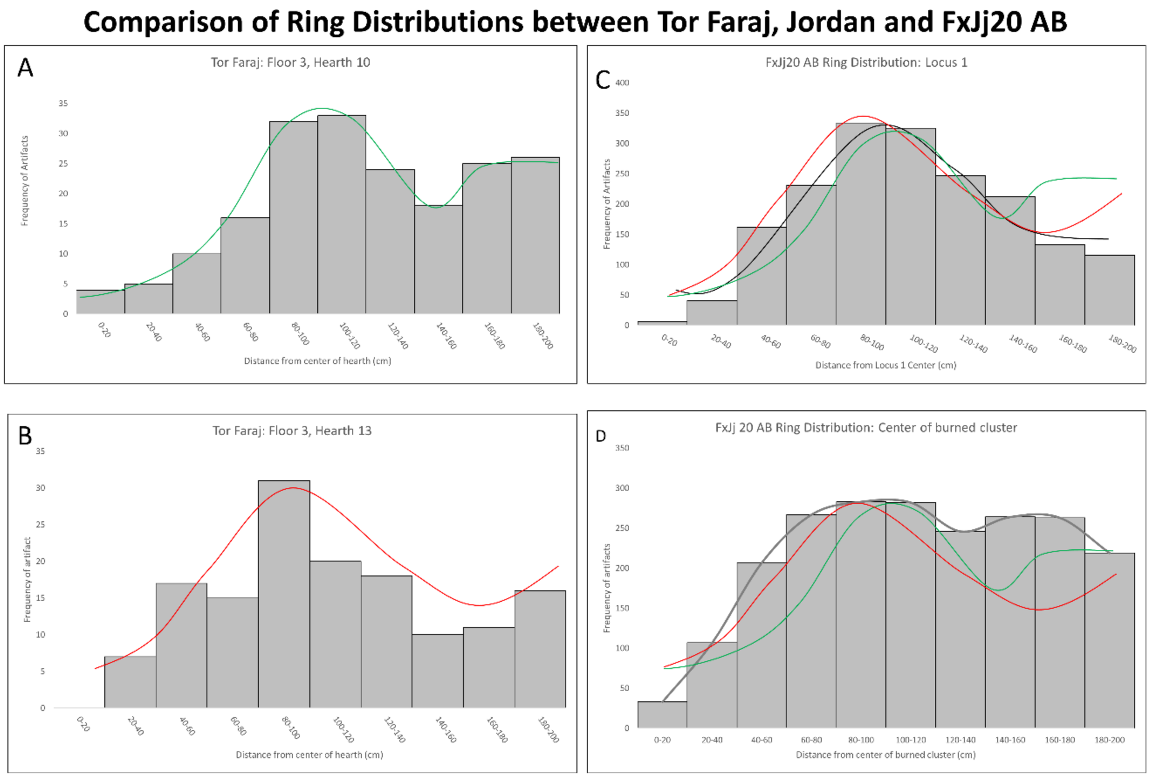

Figure 13: Comparisons of ring distributions from Tor Faraj and Fxjj20 AB. (a) Ring distribution from Tor Faraj, Floor 3, Hearth 10. (b) Tor Faraj, Floor 3, Hearth 13 (data from Henry 2012). (c) Ring distribution from FxJj20 AB, Locus 1; green line is Tor Faraj, Floor 3, Hearth 10, green is Tor Faraj, Floor 3, Hearth 13. A Kolmorov-Smirnov test shows that these distributions are not significantly different from each other (Locus 1 against H10 &H13: p=0.97; Center of burned cluster against H10 p=0.97, H13 p=1).

Another potential locus of fire activity is the area defined by the highest concentration of burned material (Locus 2, Figure 2). Using the center of the polygon describing the cluster of burned material, we measured the distribution of artifacts in concentric rings from this polygon. A comparison of these ring distributions to Floor 3 (hearths 10 and 13) at Tor Faraj, Jordan and TII2 at Pincevent, France (Figures 13d and 14c) shows that the FxJj20 AB Locus 2 assemblage is comparable to these three archaeological hearths. Kolmorov-Smirnov tests show that the sample from FxJj20 AB is consistent with the distributions found at Tor Faraj (Locus 1 and H10 and 13, p= 0.97; center of burned cluster and H10, p=0.97 and H13 p=1) and at Pincevent (Locus 1, p= 0.88; center of the burned material p=1). These Upper and Middle Paleolithic hearths are classified as Unimodal Type III, Drop Zone Dominant hearths, which bear resemblance to the ring profile at FxJj20 AB.

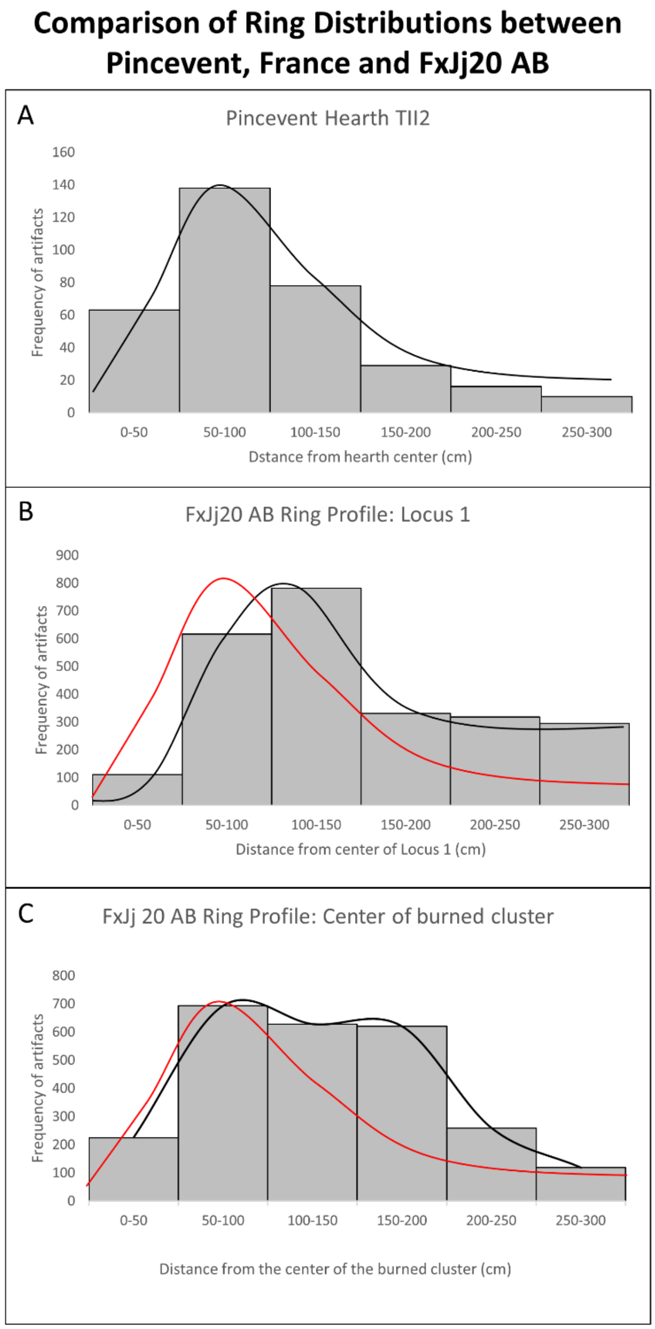

Figure 14: Comparisons of ring distributions from Pincevent and Fxjj20 AB. (a) Ring distribution from Pincevent Hearth TII2 (data from Stappert, 1997). (b) Ring distribution from FxJj20 AB, Locus 1; red line is Pincevent Hearth TII2. A Kolmorov-Smirnov test shows that these distributions are not significantly different from each other (Locus 1 against TII2, p=0.87; Center of burned cluster and PII2 p=1).

2.5 Discussion

The meticulous recovery, high-resolution mapping, and analysis of the archaeological materials found at FxJj20 AB suggest that the site has undergone weak post-depositional disturbance. None of the current analyses indicate deflation or artifact winnowing by hydraulic action. Soil micromorphology analysis suggests the site is part of a fairly rapidly aggrading deposit, with sediments brought onto the site by low-energy water. While, without refit studies, we cannot rule out a palimpsest of overlapping occupations, the vertical distribution is within the range of distribution of refitting artifacts at FxJj50 (vertical dispersion at FxJj50 is 10 – 50 cm), a similar site in floodplain deposits located a few kilometers from FxJj20 AB (Bunn et al., 1980; Kroll, 1994). The soil micromorphological analysis revealed small root and invertebrate action and minimal disturbance by larger bioturbation agents. The greatest spread in vertical distribution coincides with the high-density concentration of small (<2 cm) artifacts which could be explained by small root action disturbing and displacing these artifacts. At FxJj50, Kroll determined, through refitting studies, that the material accumulated there was likely the result of one or a few occupations on a single surface before burial, rather than multiple accumulations on several surfaces overprinting each other and intermixing (Kroll 1994). The small size of the artifacts at FxJj20 AB makes refitting studies difficult, but these are planned for the future to help resolve the question of whether the site is a single accumulation or a palimpsest of a number of accumulations on a rapidly aggrading surface.

The clustering of materials at FxJj20 AB provides some insights into hominin activities. The high proportion of flake debitage and broken or damaged flakes suggests that much of the flint knapping activities occurred on the site. Comparison to the experimental data reported in Schick (1986) indicates that the site is likely a site where flintknapping activities took place (i.e. a primary production site). The mixture of lithic artifacts and bone fragments is not inconsistent with an unspecialized camp, possibly a camp where individuals brought resources together for processing. The distribution of materials suggests the site may extend further to the east, and future excavations will shed light on the total extent of the site.

FTIR analysis shows that five rubefied sediment aggregates and at least fifty pieces of bone were heated to or above 500˚ C. Furthermore, while presently there is no established morphological definition of a potlid fracture, and the size and shape will likely vary with material type, analysis of the lithics at the site has identified a number of flakes that, based on comparison to experimental examples, are very likely potlids resulting from basalt objects being exposed to fire. Given the presence of potlids and FTIR-determined heated bone and sediment, it is reasonable to consider the other rubefied sediment aggregates to be heated, but at temperatures below 500˚ C. The limited number of heated bone fragments and sediment (0.014% of total material recovered) indicates that burning may have happened in discrete patches and was not widespread across the site, as a wildfire would have been.

More testing of materials found on the site will allow us to make a more definitive determination about the extent of fire on the site, and the thermal history of the basalts found there. Additional analysis of the sedimentological samples, both by FTIR and magnetic techniques, may be able to further clarify the extent and nature of fire at FxJj20 AB.

At the moment we have identified two main locations where fire may have been localized: Locus 1 and Locus 2 (Figure 2 and 6). Locus 1 is the low artifact density area located immediately east and north of the highest density of materials found on site, and immediately southwest of a second high-density cluster. We propose that Locus 1 may be the location of an ancient fire because of the lack of artifacts and the presence of burned bone found within this circular area and reddened chert adjacent to it. Moreover, small materials dominate the high-density cluster west of Locus 1. This is compatible with the phenomena of ‘drop zones’ as described by Binford (1983). The highest density of these specimens is found within 120-140 cm of the center of Locus 1 (Figure 12). The minimal overlap between large and small materials found on the site is consistent with the toss and drop profiles around hearths proposed by Binford (1983), and comparable to a similar distribution described for Middle and Upper Paleolithic combustion features (Alperson-Afil, Richter and Goren-Inbar 2007; Henry et al. 1996; Sergant, Crombé, and Perdaen 2006; Vaquero and Pastó 2001). The distribution profile matches the unimodal Type III, drop-zone dominant profile identified by Henry (2012) (Figure 13), and the presence of burned materials within Locus 1 at the center of this distribution further support the hypothesis that the behavioral signal found on the site may be the result of fire-control behavior by the hominins using the site. The lack of microscopic calcitic wood ash in Locus 1 deposit is explained with ethnographic analogs and the local soil conditions that do not favor calcium carbonate formation and preservation. Mallol et al (2007) demonstrated that in several open-air Hadza combustion features, even in some long-lasting ones, the amount of wood ash that is incorporated in the subsoil is surprisingly low. The general absence of calcium carbonate components and pedofeatures in the FxJj20AB soil suggests that processes that result in calcium carbonate being leached away from the top and sub-soil horizons dominate the soil environment.

The second potential location of fire (Locus 2) corresponds to the area defined by the greatest density of artifacts and burned materials. This area is where burned sediment from the site is found in conjunction with the majority of the burned bone. The position of Locus 2 to the west of Locus 1 (Supplemental Figure 11) suggests that Locus 2 corresponds to a combustion feature subsequent to Locus 1 combustion feature. The distribution of Locus 2 artifacts is consistent with ring profiles previously described for other prehistoric hearth features. A comparison of a ring profile centered on a polygon describing the highest density of burned materials (Figure 14) shows no significant difference between the ring profile centered here and the hearth features described at Tor Faraj (Henry 2012) or Pincevent (Stappert 1989) (Figure 14). Locus 2 is consistent with a fire location because of the high volume of burned materials found here. However, it is of some concern that the majority of materials found here are not burned, as would be expected for a localized fire. The mixed composition could be the result of material being moved around by animals or hominins or the result of a rapidly aggrading palimpsest site. More study of the micromorphology of the site, refitting studies, and statistical spatial analysis may shed light on post-deposition processes on the site.

Future plans include the institution of a field-based microarchaeology laboratory to facilitate experimental and archaeological investigations for microscopic charcoal and phytolith remains to improve our understanding of the nature of fire residues found in Pleistocene archaeological contexts.

Nonetheless, we can confirm the presence of burned items at FxJj20 AB and support the claims of Harris (1997), Bellomo, and Kean (1997) for potential use of fire at Koobi Fora and other Early Pleistocene localities in East Africa.

2.6 Conclusion

The integration of techniques such as soil micromorphology, FTIR, and spatial analysis allowed the identification and precise contextualization of heated archaeological materials (lithics, bone, and sediment) in the 1.5 mya old ESA context at FxJj20 AB, Koobi Fora, Kenya.

We have come to the following conclusions:

1. Spatial analysis reveals statistically significant clusters of ecofacts and artifacts indicating that the archaeological material is *in situ* and is likely the result of various hominin activities during one or a few occupation phases over a short period of time.
2. We have found evidence of fire associated with ESA archaeological material in the form of heated basalt (potlids flakes), heated chert, heated bone, and heated rubefied sediment. To our knowledge this is, to date, the earliest securely documented evidence of fire in archaeological context.
3. Spatial analysis shows the presence of two potential fire loci. Both loci contain a few heated items and are characterized by surrounding artifact distributions with strong similarities to the toss and drop zones and ring distribution patterns described for ethnographic and prehistoric hearths (Binford 1983; Henry 2012; Stappert 1998).

In summary, our results confirm the presence of fire in the Early Stone Age context of Koobi Fora FxJj20 previously documented by Harris (1973, 1997). In addition, our findings at FxJj20AB support the hypothesis of a close association of fire residues with hominin activities. To test the hypothesis of an anthropogenic origin of the fire at FxJj20 AB, more intensive sampling for FTIR, soil micromorphology and other microscopic remains such as micro-debitage, micro-charcoal and phytoliths, is needed. In fact, our work demonstrates that a recovery strategy designed to retrieve and map as much burned and unburned archaeological material as possible coupled with high resolution spatial analysis has great potential to provide important information on the nature of the association of the archaeological record with fire in primary contexts of great antiquity.

Chapter 3: Hominin fire use in the Okote Member at Koobi Fora, Kenya: new evidence for the old debate

This chapter has been submitted for publication and is under review at the Journal of Human Evolution for publication in association with a special issue on research in the Okote Member at Koobi Fora

Author List: ***Sarah Hlubik***[1], *Russell Cutts*[2], *David R. Braun*[3], *Francesco Berna*[4] *Craig Feibel*[1], *John W.K. Harris*[1]

1. Rutgers, The State University of New Jersey, New Brunswick, NJ

2. University of Georgia, Athens, GA

3. The George Washington University, Washington, DC

4. Simon Fraser University, Burnaby, BC, Canada

3.1 Introduction

Pyrotechnological skill represents a major shift in hominin behavior, allowing for an expansion of food resources, protection from nocturnal predators, and an extension of socializing hours in a day. The advent of this major behavioral change has been proposed by some to begin 1.7-1.5 million years ago (Ma). This controversial claim has been debated for several decades. The discovery of rubefied, consolidated sedimentary features found at the sites of FxJj20 East and FxJj20 Main, Koobi Fora, Kenya dated to 1.5 Ma represented a major event in this debate (Harris, 1978, 1997; Clark and Harris, 1985; Barbetti, 1986; Brain, 1993; Bellomo, 1994b; Alperson-Afil and Goren-Inbar, 2010; Wil Roebroeks and Villa, 2011). At the time of their discovery, these sediments represented some of the most convincing evidence for fire with a solid chronometric control. Paleomagnetic testing and phytolith analysis of these patches indicated suggestive, but equivocal evidence for fire (Bellomo, 1994b; Bellomo and Kean, 1997, Rowlett, 2000). Since the time of these initial studies, investigations of ancient evidence of the use of fire have advanced steadily and many previous claims have come under question (Roebroeks and Villa 2011). This has prompted criticism regarding the possibility and potential consequences of fire as part of the hominin behavioral repertoire in the Early Pleistocene (Carmody and Wrangham, 2009; Carmody et al., 2011; Clark and Harris, 1985; James, 1989; O'Connell and Hawkes, 1999; Roebroeks and Villa, 2011; Sandgathe et al., 2011; Wrangham et al., 1999). Here, we will review the evidence for fire in the Early Pleistocene archaeological record of Koobi Fora, and present new evidence for fire in the Okote Member of the Koobi Fora Formation. We discuss ongoing investigations, both archaeological and experimental, that may shed light on the presence or absence of fire in the archaeological record and discuss the ramifications of hominin control of fire on the behavior and morphology of Pleistocene hominins.

3.1.1 Biological Evidence for the Control of Fire

The hominin fossil record documents the changes between early *Homo* (e.g. *Homo habilis*) and later *H. erectus*. Among these changes are overall larger body size and smaller teeth relative to body size (Walker and Leakey, 1993; Aiello and Wheeler, 1995; Aiello and Key, 2002; Aiello and Wells, 2002; Evans et al., 2016; Zink and Lieberman, 2016). Some have suggested that early *H. erectus* specimens found in the Early Pleistocene have a smaller, less complex gut as inferred from the post-cranial material of hominins associated with *H. erectus* (Aiello and Wheeler, 1995; Wrangham et al., 1999; Aiello and Key, 2002; Aiello and Wells, 2002; Wrangham and Conklin-Brittain, 2003). Taken together, these indicate that *H. erectus* was capable of extracting more energy from its food than its predecessors extracted. Smaller teeth indicate that foods were likely softer and smaller overall masticatory apparatus supports this proposition. An increase in meat eating has previously been proposed for the reduction in tooth size and increase in body size, but this is questioned when energetic needs are taken into account (Shipman and Walker, 1989; Aiello and Wells, 2002; Wrangham and Conklin-Brittain, 2003). Studies of modern hunter gatherer populations indicate that plant foods, not meat, make up the majority of calories consumed, particularly because hunting returns can be incredibly variable (Hawkes et al., 1991). Raw vegetable foods may be readily available, but energetic returns increase on all of these food items when they are cooked (Wrangham et al., 1999; Lawlor et al., 2003; Wrangham and Conklin-Brittain, 2003; Carmody and Wrangham, 2009). Additionally, many plant foods are made up of starches too complex to be digested raw by humans and some have defense mechanisms such as toxic substances (Stahl, 1984). Cooking breaks down complex starches into simpler sugars and denatures toxic substances within plants (Stahl, 1984). Studies have documented that people eating only raw vegetable diets experience energy deficiencies (Koebnick et al., 1999).

It has also been suggested that the control of fire in the Early Pleistocene is tied to widespread environmental manipulation (Glikson, 2013). In this scenario, hominins using fire are proposed architects of landscape change and grasslands maintenance, and key actors in the stabilization of the savannah biome in East Africa (Glikson, 2013). Fossil wood studies indicate an increase in fire prevalence on the landscape beginning around 1.9 Ma in the Omo region (Dechamps, 1984) which ecologically supports the argument that fire may have been an important factor in shaping present savannah environments (Bleige-Bird 2015).

The prevalence of wildfire on the landscape would have allowed early hominins to experience fire regularly. This may have provided the context of the earliest interactions between combustion features and hominins. Among primates, modern savannah-dwelling chimpanzees have good knowledge of the mechanics of wildfire and forage near these fires while monitoring them (Pruetz and LaDuke, 2010). Vervets in the Okavango Delta region have been observed foraging in fired patches, after wildfire has moved through an area (Herzog et al., 2015). Modern Australian Aboriginal populations use controlled burns to substantially increase their returns on foraging in the Australian outback (Bliege Bird et al., 2008).

The body fossils of Pleistocene hominins suggest to some that hominins had controlled use of fire (Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Carmody and Wrangham, 2009; Wrangham, 2009; Wrangham and Carmody, 2010; Carmody et al., 2011), and some researchers have suggested that fire was a prerequisite for the consistent habitation of environments outside of equatorial and tropical regions (Gowlett, 2006; Gowlett and Wrangham, 2013). However, many Paleolithic archaeologists skeptical about the early origins of pyrotechnology (James, 1989; Sandgathe et al., 2011; Roebroeks and Villa, 2011). This is largely because of the dearth of solid evidence that links tightly delineated localities holding concentrated evidence of combustion features, sometimes constrained by dirt or rock berms, to Pleistocene hominins, and the lack of clear cultural evidence for the use of fire until at least 0.5 Ma.

3.1.2 Early Pleistocene Evidence of Combustion Features

Several Early Pleistocene sites in East and South Africa, exhibit evidence for fire in prehistory (Harris, 1973, 1982, 1997; Clark and Kurashina, 1979; Barbetti et al., 1980; Gowlett et al., 1981; Isaac, 1982; Clark and Harris, 1985; Barbetti, 1986; Brain and Sillen, 1988; James, 1989; Brain, 1989; Bellomo and Kean, 1997; de la Torre, 2011; Berna et al., 2012). Table 3 presents a brief summary of the data associated with fire at early African and Southwest Asian sites. Evidence of combustion at these sites is not controversial. However, the ability to discern, or even infer, the anthropogenic nature of these materials as opposed to attributing it to natural events is still a matter of debate (James, 1989)..

Table 3: Table of sites showing evidence for early fire in Africa and Israel.

SITE	DATE	EVIDENCE
Gadeb, Ethiopia [1, 2, 5]	1.45 – 0.7 mya	Discolored ignimbrite artifacts with thermoremnant magnetism (TRM) consistent with being heated
Middle Awash, Ethiopia [1, 2, 5]	>0.6 mya	Circular discolored sediments
Swartkrans, South Africa [5, 6, 7]	1.2 mya	Burned bones
Chesowanja, Kenya [3, 5]	1.42 mya	Discolored sediments in association with Oldowan artifacts
Olduvai Gorge, Tanzania [8]	1.2 mya	Thermally altered artifacts (potlids, discoloration)
Wonderwerk Cave, South Africa [12, 13]	1.0 mya	Ashed plant remains, burned bones
Gesher Benot Ya'aqov, Israel [9, 10, 11]	0.78 mya	Charcoal, thermally altered micro and macro artifacts

These sites show evidence for fire associated with hominin occupations in the Early Pleistocene and Early Middle Pleistocene. 1. Clark and Kurashina, 1979; 2. Barbetti et al., 1980; 3. Gowlett et al., 1981; 4. Harris, 1982; 5. Clark and Harris, 1985; 6. Brain and Sillen, 1988; 7. Brain, 1993; 8. Ludwig, 2000; 9. Goren-Inbar et al., 2004; 10. Alperson-Afil et al., 2007; 11. Alperson-Afil and Goren-Inbar, 2010; 12. Berna et al., 2012; 13. Thibodeau, 2016

There is currently no consensus as to how this evidence of combustion was created. Archaeologists have relied on various lines of evidence to support human control of fire. This includes baked clay clasts, thermally-altered stone, and/or burned bone with a close spatial association with *in situ* evidence of hominin activity (Shahack-Gross et al., 1997, 2014; Berna and Goldberg, 2007; Karkanas et al., 2007; Berna et al., 2012).

3.2.3 Evidence of Combustion Features in the Koobi Fora Formation

The present study reviews the evidence for hominin association with combustion features at the FxJj20 site complex from the Okote Member of the Koobi Fora Formation. The Okote Member is bounded by the Okote Tuff Complex (1.61 Ma), at its base, and the Chari Tuff (1.38 Ma), at its top (Brown and Feibel, 1986; Brown and McDougall, 2011). The FxJj20 site complex is a series of archaeological localities that are located in paleontological Area 131 in the Karari Ridge region of the Koobi Fora Research area (Figure 15). Extensive excavations in the FxJj20 site complex recovered tens of thousands of stone artifacts from floodplain silts (Harris, 1978, 1997).

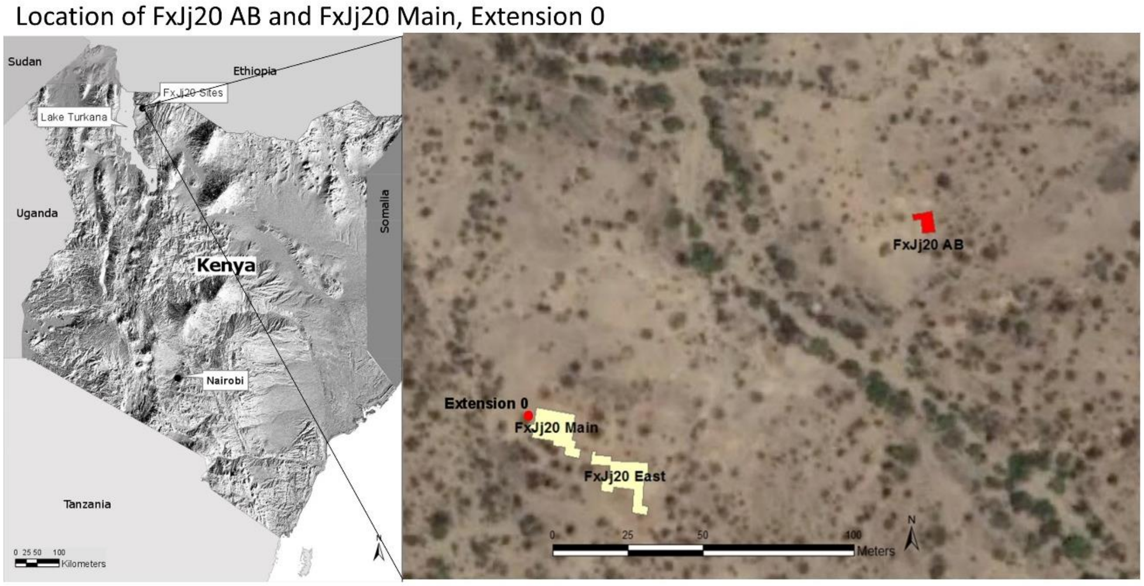

Figure 15: Location of FxJj20 Site complex. FxJj20 East and Main were fully excavated in the 1970s and 1980s; FxJj20 AB was discovered in the 1970s and was reopened for excavation in 2010. Excavation at FxJj20 AB is ongoing. FxJj20 Main – Extension 0 is located outside the northeast corner of FxJj20 Main, was discovered in 2013, and a test excavation was done in 2015.

The site complex includes two localities that are directly adjacent to each other (FxJj20 Main and FxJj20 East) and then a subsequent locality (FxJj20 AB) that is located approximately 100 meters to the NE of the FxJj20 Main and East (Harris, 1997). At FxJj20 East and FxJj20 Main, concentrations of consolidated, rubefied sediment were found in an arc-like pattern during excavation in the 1970s (Harris, 1978, 1997; Clark and Harris, 1985). Researchers initially postulated that the concentrations might be from fire. A review of the evidence for the presence of fire at Fxjj20 East and FxJj20 Main is found in Table 4.

Table 4: List of evidence from the Koobi Fora Formation for the presence of fire.

EVIDENCE	AUTHOR	CONTENTION
Bowl-shaped cross-section	Clark and Harris, 1985	Result of iron-staining or fungus
Paleomagnetic signature of at least one patch is consistent with burning	Bellomo and Kean, 1997	Most patches had inconclusive results
Spatial association of artifacts with patches	Bellomo, 1994a, b	Movement of artifacts by post-depositional processes
Mixture of grass and wood phytoliths within patches as compared to surrounding sediments	Rowlett, 2000	Modern contamination of phytoliths
Thermoluminescent results of sediment consistent with having been heated	Rowlett, 2000	Exposure of sediments to natural light; patches excavated 30+ years prior to testing

The locality of FxJj20 AB was also initially excavated in the 1970s (Harris 1973, 1997). These preliminary excavations noted the presence of rubefied sediments. These were similar to the patches of rubefied sediments described from FxJj20 Main. The large patches found at FxJj20 Main and East were never observed at FxJj20 AB. Until 2010, no large-scale excavations have taken place in the FxJj20 site complex since the close of excavations in 1979.

In this study, we attempt to take a multi-facetted approach to identifying features that may be associated with hominin control of fire at the FxJj20 Sites. We provide preliminary data on a variety of the methods described above that may be able to identify combustion features in open-air Early Pleistocene contexts. These methods show that it may be possible to identify thermally altered materials in the deep past. We will then discuss the potential of these new proxies for pyrotechnology in deep antiquity. Finally, we review new methods of identifying potential localities where the control of fire is associated with ephemeral hominin occupation. A single locality with evidence of hominin use of fire can be dismissed as a coincidence of natural factors, but the connection of several sites, particularly within a small region of the landscape, that are all studied using a similar excavation and analysis techniques, can bolster the argument that fire was used by hominin ancestors in the deep past.

3.2 Background to the study:

3.2.1 FxJj20 Site Complex

Excavations at FxJj20 AB implemented a series of excavation techniques that were designed to increase the recovery of the smallest fraction of the archaeological record. Excavation involved the use of only small tools, to recover small materials in their original provenience. This methodology allows for the identification of high concentrations of small artifacts without the need to average whole or quarter squares and improves the accuracy of spatial analyses. This methodology led to the recovery of a high-density of small lithic materials. The highest density of materials was noted east of the largest concentration found in the original 1973 excavation. At the center of this high-density area, an anomalous low-density circle was identified. This low-density anomaly (Locus 1, Figure 16) became the focus of further investigation during subsequent excavations. Possible explanations for this juxtaposition of high-density scatters and anomalously low densities of material include water flow, animal burrows, or ancient tree stumps. To determine whether this pattern was the result of natural phenomena or the result of hominin activity, we investigated this area further (Alperson-Afil et al. 2009.

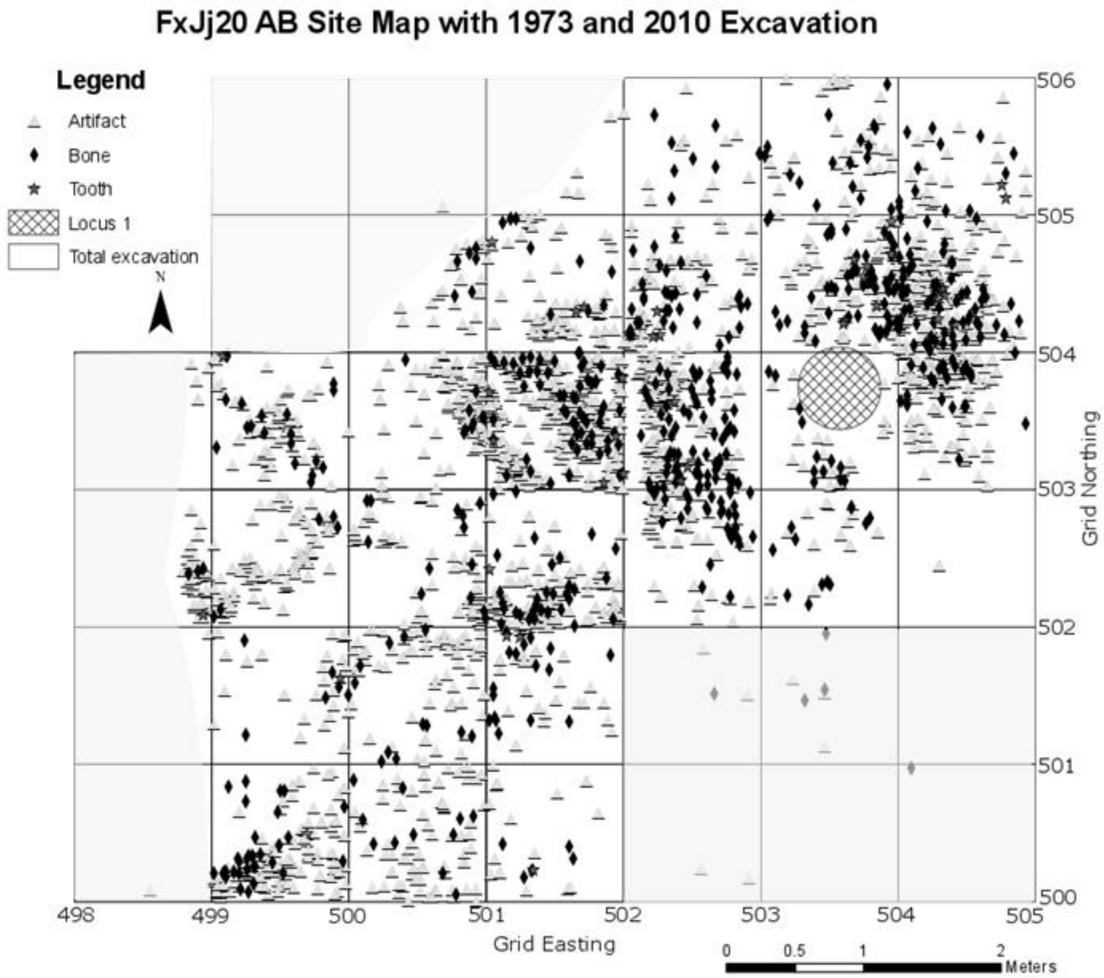

Figure 16: Location of materials after the 2010 excavation season. Locus 1 was identified as an anomalously empty space within a dense cluster of artifacts after the 2010 field season and subsequently partially excavated and sampled. Grey shaded areas represent unexcavated squares and modern erosional surfaces; materials found within these areas are surface collected.

To identify other potential indications of pyrotechnology, we initiated surface survey along Okote Member sediments within a roughly 2 km radius of the FxJj20 site complex. Photographs, site descriptions, pace-and-compass transects were assembled. If warranted, artifacts/sediments were collected, bagged, and labeled, and curated at the National Museums of Kenya in Nairobi. A 2013 survey of the areas surrounding the FxJj20 East and Main sites revealed an additional rubefied patch of sediment approximately 15 meters to the north and west of the original FxJj20 Main site. The feature, hereafter described as FxJj20 Main-Extension 0 (FxJj20 MExt-0), is stratigraphically similar to the original FxJj20 Main site. This feature is eroding due to modern bioturbation (goat-path) across its northern edge. This isolated area of rubefied sediment included several artifacts. Some of these artifacts are consistent with the Developed Oldowan/Karari Industry. One artifact in particular (a basalt hammerstone) had indications of fracture usually associated with high temperatures (i.e. "potlid") as well as the refitting angular fragment. This locality provides an indication of the extent of these possible landscapes that preserve ephemeral, yet identifiable, instances of pyrotechnology.

3.2.2 Experimental work

A number of experimental fires were undertaken to produce a reference collection of burned materials common to the area as a comparison to archaeologically produced artifacts. Experiments concentrated on volcanic rocks (ignimbrites and basalts), as these are the most commonly identified materials on the FxJj20 sites. It is difficult to visually identify thermal alteration on basalt and ignimbrite, as these materials do not display any obvious color change. They do fracture as the result of a rapid rise in temperatures. One such type of fracture is commonly known as a "potlid" (Purdy and Brooks, 1971; Patterson, 1995), and is characterized by an irregular ventral surface with an uneven appearance (Figure 17). None of the features commonly associated with conchoidal fracture are evident on potlids (bulb of percussion, point of percussion, or platform). Potlids are often thickest at their center. These material are often used to identify the presence of high temperature events at an archaeological site (Purdy and Brooks, 1971). However, potlid fractures are not unique to archaeological materials and often natural stones can fracture when exposed to high temperatures over long periods of time (Patterson 1995; Jackson 1998).

Example of a potlid from experimental field burns

Figure 17: Example of a potlid from experimental field burns. Note the small size, uneven shape, and the irregular surface.

Our experimental archaeological agenda identified a number of curved fragments associated with knapped materials exposed to long-duration high-temperature fires. These types of fragments were never recovered with experimental fires that had unknapped stone inside them. These distinctive angular fragments are infrequently produced during knapping activities. We identified features of these distinctive angular fragments, that we term thermal curve fractures (TCF), that differentiate between those materials frequently associated with standard knapping and those that are the product of exposure to high temperatures. We provide some preliminary data on the morphology of these fragments that led us to investigate this phenomenon further with more experimental work.

3.3 Methods

There are two major methodological aspects of study. The first is excavation and sampling of the sites FxJj20 AB and FxJj20 Main Ext-0, including excavation and sampling for micromorphological, and spectral studies. The experimental and actualistic studies make up the second major portion of study we will discuss here. The experimental work helps to establish a reference collection of burned materials, including stone and sediment.

3.3.1 FxJj20 AB:

The excavation of FxJj20 AB was undertaken through generally standard procedures: removal and screening of sediment, while preserving the original location of bone and artifacts. Excavation proceeded in 5 cm levels, and all materials found were measured using a total station, running EDM Mobile (McPherron and Dibble, 2011), which precisely records the location to millimeter accuracy (McPherron, 2005). Materials with a discernible long axis are recovered with two sets of coordinates at either end of the long axis to facilitate orientation analysis. The high-fidelity recovery methodology allows us to make determinations about site formation processes that can be corroborated or contested by the micromorphology.

Targeted micromorphological sampling was undertaken to determine the specific post-depositional history of the site, and identify any microscopic evidence for fire, in the form of ashed plant remains, siliceous aggregates, or microscopic charcoal (Goldberg and Berna, 2010). These samples were between 2-4 cm in width and thickness, and between 3-7 cm in length. These oriented samples were cut from the excavation, jacketed in plaster, and then removed.

The area previously described as Locus 1 was excavated in cross-section. One-quarter of the western half was excavated, and micromorphological samples were taken from the other quarter in the western half of Locus 1. The other half of this feature is intact to enable future sampling. If Locus 1 represents an animal burrow or a tree, then we expect the fabric of the micromorphology to be distinct from micromorphological samples from nearby squares. In the absence of major bioturbation, we expect that color and texture of the sample will be similar to the sediment that surrounds Locus 1.

Fourier Transform Infrared Spectroscopy (FTIR) can be used to determine the thermal history of sediment from an archaeological locality (Berna and Goldberg, 2007; Goldberg and Berna, 2010;

Berna et al., 2012). Samples of rubefied and non-rubefied sediment were collected for FTIR analysis. A sample of non-rubefied sediment, from outside the site, at the same stratigraphic level was also taken to be used for experimental heating of the sediment. The sample was burned in a muffle furnace to specific temperatures to create a reference collection specific to the sediment from FxJj20 AB. These experiments serve as a reference for the identification of sediments that have been exposed to high temperatures.

In addition to sediment, FTIR analysis was used to analyze bone and stone from FxJj20 AB. The thermal history of bone can be accurately determined using FTIR analysis (Shahack-Gross et al., 1997; Karkanas et al., 2007). Additionally, experimental work with basalt from the Turkana Basin has been used to create a reference collection of burned and unburned material to which the archaeological samples can be compared.

To identify heterogeneity in the density of artifacts in the archaeological horizon it was necessary to employ spatial analytical techniques. One spatial analysis technique is particularly suited for identifying areas where densities of materials are greater than would be expected by random chance. This technique, called Optimized Hot Spot Analysis (OHSA), can detect spatially significant concentrations (Getis and Ord, 1992) . We implemented this analysis on the distribution of material from the archaeological site along the X-Y (i.e. northings and eastings) plane as well as the Y-Z (northings and depth) plane. This allowed for an investigation of the vertical and horizontal distribution of material. OHSA uses the Global Moran's I statistic to identify clusters which are significantly different from random. OHSA prevents false identification of patterns by lowering the threshold for significance in particularly dense concentrations of material (e.g. p = .05 or .001) and can be run with or without a weighting variable in the analysis. Without a weighting variable, the program analyzes all material to identify clusters that are different from random. With a weighting field, the program analyses material in relation to the weighting variable. Weighting data can be any ordinal data. We used the OHSA technique to understand multiple aspects of the density of materials within FxJj20 AB. A first analysis did not use a weighting field to determine whether artifacts, bone, and heated materials are clustered in particular locations within the site. Subsequent OHSA analyses focused on the size of the artifacts as a weighting variable. This analysis allows us to determine if the distribution of finds along the site are related to the size of the materials. If smaller artifacts are concentrated near other indicators of combustion (burnt bone, rubefied sediments) this may indicate the presence of a feature that is similar to combustion features seen in later time periods that indicates the presence of structure within the archaeological site. These have previously been described as “toss and drop zones” that were recorded in ethnographic studies (Binford, 1980, 1981, 1983).

We expect that, if fire is associated with hominin behavior, then we will see high frequencies of artifacts spatially associated with burned material. We expect to see lithics and bone with evidence of thermal alteration to be found with evidence of burnt sediment. We expect to see the highest frequencies of burned material to be spatially clustered.

3.3.2 Experimental work:

While actualistic studies and ethnoarchaeology are not exact proxies for past human behavior (Bettinger, 1991), it would also be incorrect to presume that they are not informative of such behaviors. We performed a series of actualistic studies focused on the reaction of lithic materials at different temperatures within fires. These experiments were targeted at identifying temperatures associated with the (hominin) control of fire. In particular, we are pursuing an understanding of how stone from the Turkana Basin, which was available to hominins in the

Pleistocene, is affected by long duration, ground level fires. These experiments are distinct from heat-treatment, which improves the flakeability of stone material (Domanski and Webb 1994). Rather, we intend to investigate the effects of direct application of heat to stone material, as this would mimic what would happen if a hominin was knapping around the fire. Experiments proceeded by collecting unmodified nodules and cobbles (e.g., basalt, ignimbrite, chalcedony, etc.) from modern conglomerates in ephemeral rivers of the Turkana Basin, northern Kenya. Both unknapped (i.e. un-worked, unmodified) cobbles/nodules and knapped materials (flakes, core remnants, bifaces) are fired. Knapped and unknapped pieces are never included in the same firing event. Detached pieces (Harris, 1997) were selected from each type of distinct material in attempt to conform to roughly standardized sizes (dimension and weight). These were intended to represent useful size and shape flake tools, as well as “typical” knapping debitage.

Fires were constructed using local wood in a pyramidal manner on sand or silt, swept clean of debris, approximately one meter in diameter. Some fires were built on top of arranged lithic materials, while other fires had lithics introduced during the burn. Some lithics were introduced at the height of temperature for the fire, while some fires were allowed to cool below 450°C (determined by IR temperature thermometer) prior to lithics being introduced. Each fire was allowed to cool for at least 24 hours prior to excavation, which consisted of removing remaining fuel debris and charcoal, carefully sweeping ash from burnt experimental lithic components (for photographic purposes), systematically collecting fired materials and screening underlying sediments. Some fires also included systematic collection of samples for FTIR and microstratigraphic analysis.

In addition to noting changes in material surface, luster, strength and friability of the stone pieces, photography also allowed documentation of fracture patterns and the spatial distribution of specimens that occurred during firing events. An IR temperature thermometer (Sper Scientific 800103 IR Thermometer) indicated that all fires peaked above 550°C. Recovered experimental materials were sorted and counted, described. We recorded details of the specimens (surface textures, cracking) as well as measurements of the specimens (using a digital caliper to the nearest 10^{th} of a cm.). Experimentally fired materials are curated in the Archaeology Division of the National Museums of Kenya, Nairobi.

To determine whether the curved fragments noticed during the experiments were a result of human behaviors and fire use, we designed a set of experiments to produce these fragments and compare them to curved angular fragments resulting from only knapping activities. To begin, a number of lithic materials, including chert, chalcedony, ignimbrite, and basalt, were knapped. Each material was knapped separately and the debitage was searched for curvilinear angular fragments, which were collected for future comparison to curved pieces from fired lithic materials. Larger, complete flakes from these knapping sessions were then exposed to fires at temperatures above 550°C for several hours. After cooling, fires were excavated using a fine mesh (2 mm) screen and all fragments were collected. Fragments from the experimental knapping were measured. We focused measurements on maximum length, maximum width, curve height and calculated curvature height in accordance with Andrefsky's (1986) techniques, wherein Euclidean geometry calculates variables from angle length, angle depth and thickness at midpoint. In ascertaining the peculiar symmetry of these TCFs, we also measured width and thickness at each end, and at the mid- and quarter-points along the length to determine the evenness of width and thickness across the fragment (Eren and Lycett, 2012; Presnyakova et al., 2015). We compared the evenness of the experimentally produced TCFs to curvilinear debitage produced during knapping exercises using width and thickness measurements. We calculated the average width and thickness across each experimentally produced piece and then calculated the average deviation of these measurements from the mean within an individual specimen. This deviation of the various width and thickness measurements within an individual specimen were then aggregated to derive an evenness value for each specimen. This evenness measurement was averaged to get a measure of evenness for the whole sample. The evenness of thickness and width of all TCFs was compared to the evenness of all curvilinear debitage using a two-tailed Student's t-test.

A review of the angular fragments from the FxJj20 Main and FxJj20 AB collections in the National Museums of Kenya in Nairobi was undertaken to identify curvilinear angular fragments (potential TCFs) in archaeological collections. Curved fragments identified in these collections were measured in the same way as the experimentally produced fragments. The measurements of the archaeological fragments were compared to the experimentally produced fragments using Student's T-tests and Principal Components Analysis.

3.4 Results

3.4.1 Archaeology

Excavations of FxJj20 AB, between 2010 and 2015, yielded over 3000 artifacts and bone fragments (Figure 18), the majority of which are small debitage pieces. There are 2893 *in situ* artifacts collected with three-dimensional coordinates. The breakdown of these artifacts is provided in Table 5. Bone found on the site is mostly NID mammal and reptile fragments (a complete faunal analysis is still underway). The original excavations also yielded a large number of stone and bone fragments, as well as some larger tools typical of the Karari Industry (Harris, 1978, 1997).

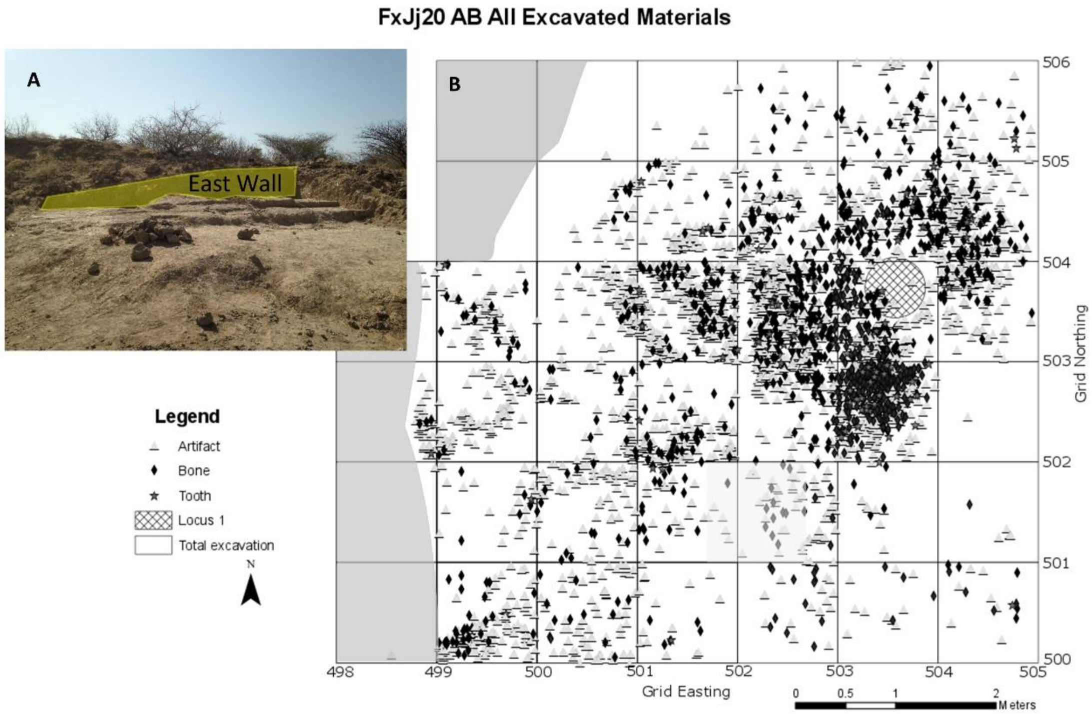

Figure 18: (a) Photograph of site facing southwest across site. (b) Location of all excavated materials at Site FxJj20 AB. Grey shaded areas represent erosional surfaces.

A breakdown of the stone material included debitage pieces, whole flakes, broken flakes, cores, and potlid flakes (Table 5). An OHSA of these materials indicates one very large cluster roughly in the center of the excavated area near Locus 1, with several small clusters found toward the south and west of the site (Figure 19). Analysis of the materials in cross section (viewing the site from North wall of the excavation) indicates that the site is found on a slight slope (~5%) running east to west, but an analysis of size of materials indicates that this slope did not likely affect the positioning of material within the site (Hlubik et al., 2017a). Smaller artifacts are found uphill (in squares 504N/503E and 503N/504E) of larger artifacts (in squares 503N/502E, 504N/500E, and 501N/500E, see Figure 20). Many artifacts on the site (40%) are 20 mm or less in maximum dimension. This high frequency of smaller artifacts suggests that substantial size sorting or winnowing was not part of the post-depositional history of the site (Schick, 1986, 1987).

Table 5: List of all excavated materials from FxJj20 AB

Excavated Materials	**Count**
Cores	85
Cobbles	16
Flakes	1435
Whole flakes	795
Broken flakes	640
Flakes with potlid evidence	3
Angular Fragments	1372
Debitage	1328
Potlids	44
Pebbles	52
Hammerstone	9
Bone	1242
Tooth	102
Total	4313
Raw Material	**Count**
Basalt	2807
Quartz	19
Ignimbrite	60
Chert	58
Chalcedony	21
Feldspar	4

Optimized Hot Spot Analysis of all excavated materials

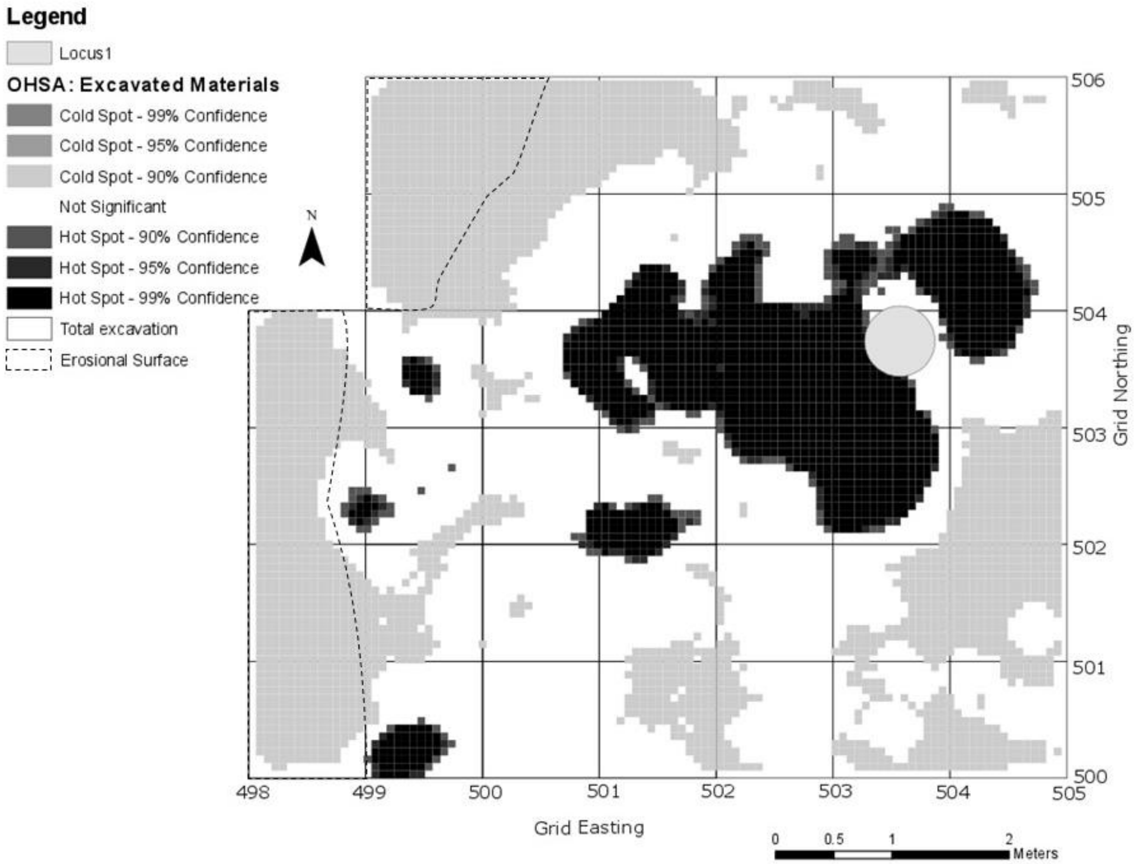

Figure 19: Optimized Hot Spot Analysis of all excavated materials. Most bone and artifacts are concentrated around Locus 1, with some smaller concentrations found further away to the south and west of Locus 1. Areas with no fill are not different from random. Dotted lines represent the erosional surfaces; cold spots located here are the result of data loss as opposed to a lack of material found there (from Hlubik et al., 2017a).

Optimized Hot Spot Analyses of size-weighted artifacts, burned material, and bone

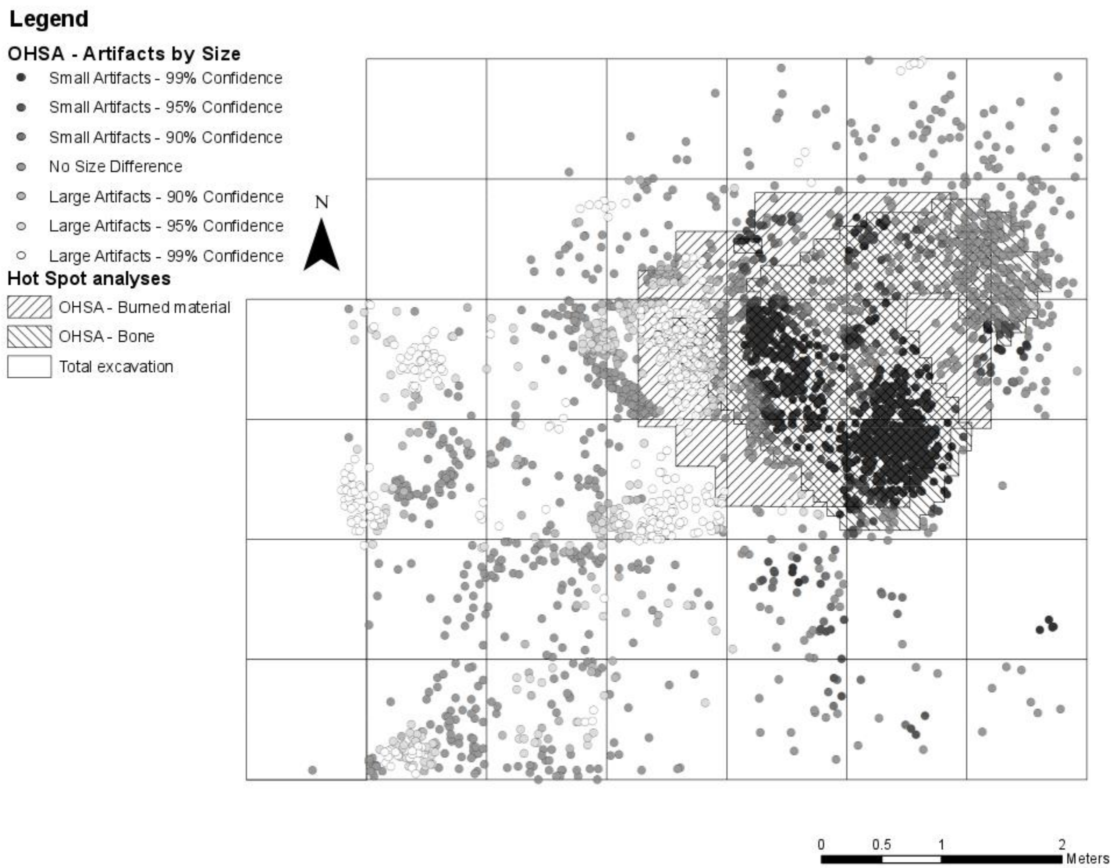

*Figure 20: Optimized Hot Spot Analyses (OHSA) of size-weighted artifacts, burned material, and bone. This shows that burned material, bone, and smaller artifacts (darker colored circles) are clustered together around Locus 1 (*p *= 9.77178E-44), while larger artifacts (lighter colored circles) are clustered away from Locus 1, and not associated with significant clusters of bone or burned materials. No cold spots of bone or burned material were identified on-site.*

Even mild winnowing of materials from sites will depress the number of small debitage pieces found on a site (Schick, 1986). A Chi^2 comparison of eight of the experimentally produced sites from Schick (1986) that were moderately disturbed by the experimental treatment (hydraulic action or winnowing) yielded no similarity to FxJj20 AB either before or after experimental treatment (Table 6). A closer look at these results using Freeman-Tukey deviates shows that for all sites, except in a few instances, all size classes are significantly different from the archaeological assemblage (Table 7), both before and after the experimental treatments. Differences in the experimental assemblages devised by Schick before treatment and FxJj20 AB indicates that FxJj20 AB is neither an instance of a single knapping activity, nor is it similar to the experiment designed to mimic several activity areas (Schick Site 36). The archaeological horizon at FxJj20 AB may extend to the east and south of its current boundaries. Dissimilarities of FxJj20 AB and experimental sites after hydraulic action indicates that winnowing from water disturbance is not the likely culprit for the pattern of materials seen at FxJj20 AB. Fragments of the smallest size category are overrepresented (0-1 cm and 1-2 cm) in the archaeological site compared to the moderately disturbed experimental sites.

Analyses of the orientation of the originally excavated material indicates no preferred orientation of artifacts (Clark and Harris, 1985; Harris, 1997). An analysis of the orientations from the newly excavated materials from FxJj20 AB indicates no preferred orientation (McPherron 2005) of the materials, but supports the interpretation that the material was deposited on a slight slope (Hlubik et al., 2017b). Micromorphological analysis of the blocks from within the excavation indicates that the site was buried quickly, likely as the result of seasonal or semi-seasonal flood events (Hlubik et al., 2017a). Figure 21 shows that the materials throughout the sedimentary column are similar, and well mixed probably due to minor root action, and there are no indications of major bioturbation events, such as burrows, termite mounds or major root action that would be expected from tree growth within the site (Hlubik et al., 2017a). Micro-channels and a few passage features (indications of the movement of small insects and small amounts of water) are seen in the thin sections (Hlubik, et al., 2017a). The fine sand and silt is poorly sorted and further indication of low-energy water deposition of sediments on the site.

Soil micromorphology at FxJj20 AB

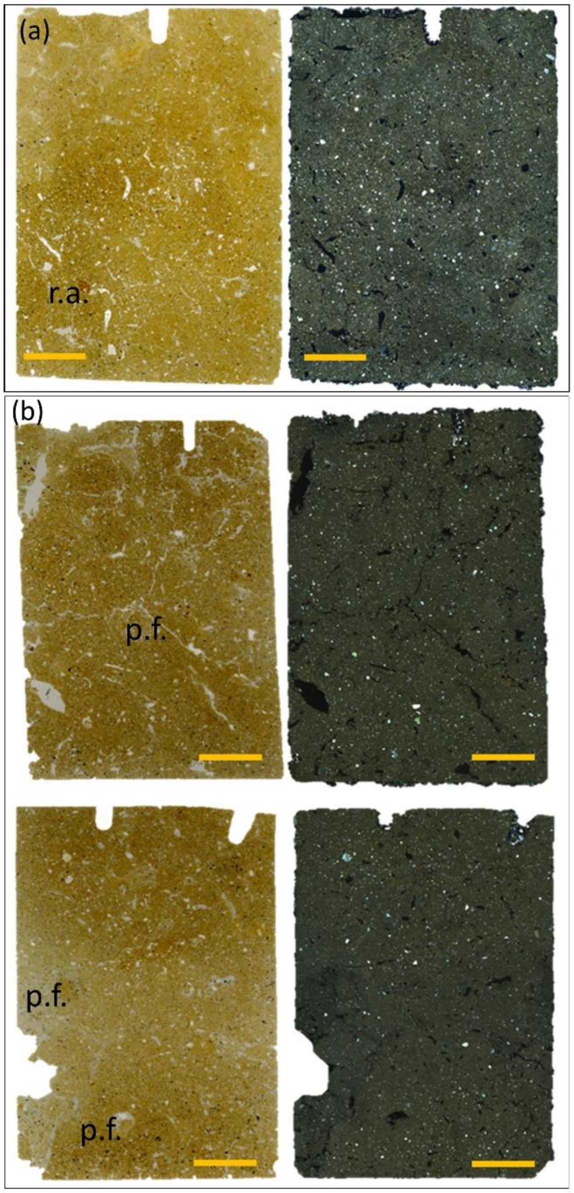

Figure 21: Soil micromorphology at FxJj20 AB. ***(a)*** *Representative cross-polarized light micrograph of the local ground mass (scale bar = 200 µm). Note the micaceous, feldspathic, and quartz composition of the poorly sorted silt and sand and the laminated clay coatings around pores and sand grains.* ***(b)*** *Plane polarized light (left) and cross polarized light (right) scan of petrographic thin sections of intact block of local soil column, catalog number 25015 (scale bar = 1cm). Note the silty clay loam texture, channel microstructure and a few passage features (p.f.). Note sediment from all three samples have similar composition and structure and contains rare rubefied soil aggregates (r.a.).*

Table 6: Chi² comparison of a selection of Schick (1986) experimental sites with FxJj20 AB, both before and after experimental treatment.

	Sample vs Expected																
Before	FxJj20 AB vs Site 25		FxJj20 AB vs Site 1a		FxJj20 AB vs Site 22		FxJj20 AB vs Site 36		FxJj20 AB vs Site 19		FxJj20 AB vs Site 20		FxJj20 AB vs Site 26/27		FxJj20 AB vs Site 24		
	Chi2	50.566	Chi2	227.32	Chi2	50.566	Chi2	76.295	Chi2	105.26	Chi2	49.001	Chi2	61.509	Chi2	50.566	
	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	
	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	
	p	<0.003	p	<0.003	p	<0.003	p	<0.003	p	<0.00	p	<0.003	p	<0.003	p	<0.003	
After	FxJj20 AB vs Site 25		FxJj20 AB vs Site 1a		FxJj20 AB vs Site 22		FxJj20 AB vs Site 36		FxJj20 AB vs Site 19		FxJj20 AB vs Site 20		FxJj20 AB vs Site 26/27		FxJj20 AB vs Site 24		
	Chi2	49.553	Chi2	276.2	Chi2	168.3	Chi2	182.36	Chi2	121.54	Chi2	52.92	Chi2	161.59	Chi2	37.412	
	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	DF	4	
	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0001	Monte Carlo	0.0002	
	P	<0.003	p	<0.003	p	<0.003	p	<0.003	p	<0.003	p	<0.003	p	<0.003	p	<0.003	

All comparisons are with sites that were moderately disturbed through experimental treatment. None of the experimental sites are statistically similar to the archaeological site, either before, or after the experimental treatment at a Bonferroni corrected p value of 0.003.

Table 7: Freeman-Tukey deviates calculated for comparison sites.

	Size class	FxJj20 AB	Site 25	Freeman-Tukey Deviate	Size Class	FxJj20 AB	Site 1a	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 22	Freeman-Tukey Deviate	Size Class	FxJj20 AB	Site 36	Freeman-Tukey Deviate
Before	0-1 cm	403	100	0.476353	0-1 cm	403	0	0.95164	0-1 cm	403	100	0.476353	0-1 cm	403	1327	0.48867029
	1-2 cm	723	130	0.684232	1-2 cm	723	21	0.977368	1-2 cm	723	130	0.684232	1-2 cm	723	1806	0.67718431
	2-4 cm	512	80	0.679381	2-4 cm	512	49	0.462209	2-4 cm	512	80	0.679381	2-4 cm	512	1116	0.67301075
	4-8 cm	140	20	0.44946	4-8 cm	140	46	-0.01895	4-8 cm	140	20	0.44946	4-8 cm	140	286	0.4447632
	8-16 cm	2	10	0.009852	8-16 cm	2	7	-0.04095	8-16 cm	2	10	0.009852	8-16 cm	2	120	0.01674737
	Size class	FxJj20 AB	Site 19	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 20	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 26/27	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 24	Freeman-Tukey Deviate
	0-1 cm	403	71	0.509472	0-1 cm	403	100	0.523718	0-1 cm	403	200	0.476353	0-1 cm	403	100	0.47635301
	1-2 cm	723	96	0.706182	1-2 cm	723	175	0.595901	1-2 cm	723	260	0.684232	1-2 cm	723	130	0.68423224
	2-4 cm	512	60	0.689694	2-4 cm	512	80	0.719436	2-4 cm	512	160	0.679381	2-4 cm	512	80	0.67938135
	4-8 cm	140	19	0.425569	4-8 cm	140	20	0.461902	4-8 cm	140	40	0.44946	4-8 cm	140	20	0.4494603
	8-16 cm	2	17	-0.05481	8-16 cm	2	10	0.016376	8-16 cm	2	20	0.009852	8-16 cm	2	10	0.00985187
After	Size class	FxJj20 AB	Site 25	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 1a	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 22	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 36	Freeman-Tukey Deviate
	0-1 cm	403	72	0.541076	0-1 cm	403	0	0.95164	0-1 cm	403	7	0.826177	0-1 cm	403	63	0.67243533
	1-2 cm	723	115	0.668172	1-2 cm	723	7	1.131101	1-2 cm	723	27	0.850365	1-2 cm	723	109	0.82515855
	2-4 cm	512	74	0.652367	2-4 cm	512	34	0.493242	2-4 cm	512	45	0.425133	2-4 cm	512	134	0.53851879
	4-8 cm	140	20	0.431777	4-8 cm	140	44	-0.15201	4-8 cm	140	16	0.292228	4-8 cm	140	55	0.31367903
	8-16 cm	2	10	0.000524	8-16 cm	2	6	-0.05712	8-16 cm	2	10	-0.1081	8-16 cm	2	35	-0.09637523
	Size class	FxJj20 AB	Site 19	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 20	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 26/27	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site 24	Freeman-Tukey Deviate
	0-1 cm	403	47	0.495945	0-1 cm	403	69	0.57675	0-1 cm	403	25	0.698073	0-1 cm	403	4	0.82209898
	1-2 cm	723	55	0.754933	1-2 cm	723	145	0.580252	1-2 cm	723	62	0.719928	1-2 cm	723	28	0.56261827
	2-4 cm	512	40	0.675366	2-4 cm	512	67	0.70717	2-4 cm	512	49	0.61662	2-4 cm	512	21	0.50794571
	4-8 cm	140	13	0.416554	4-8 cm	140	19	0.44503	4-8 cm	140	22	0.334987	4-8 cm	140	3	0.46230972
	8-16 cm	2	13	-0.0773	8-16 cm	2	10	0.004481	8-16 cm	2	17	-0.11134	8-16 cm	2	2	0.00030165

Freeman-Tukey deviates demonstrate which categories are driving the major differences for chi-square tests. Results close to zero mean that category is responsible for less of the difference between samples, while results away from zero indicate that category is responsible for more difference; results greater than 2 or less than -2 are statistically rare events. This table shows that are no statistically rare categories and that the majority of the difference between populations is being generated by smaller sized materials.

Rubefied sediment occurs throughout the site, intermixed within the archaeological layers, but is concentrated in the densest cluster of artifacts and in the southeastern squares of the excavation. Five samples of rubefied sediment, with three dimensional coordinates, and four samples from level bags, have been tested with FTIR and have been determined to be burned at temperatures over 550^{o} C (Hlubik et al., 2017a). All rubefied sediment found during excavation is mapped to allow for spatial analysis. Only a subset of rubefied sediment has been collected.

Most small materials (<2 cm.) are found within the largest cluster of artifacts west and south of Locus 1, in squares 504N/503E and 503N/504E, while other clusters further away from Locus 1 have larger materials (Figure 20). FTIR testing of sediment and bone has revealed a concentration of burned materials near Locus 1, with a piece of burned bone coming from within the excavated quarter of Locus 1 (Hlubik et al., 2017a). The concentration of burned material in this location further supports the idea that fire and hominin behavior were associated on this site in the past. An analysis of all bone, rubefied sediment and artifacts shows that the largest concentration of bone and rubefied sediment is clustered with the smallest artifacts (Figure 20). The populations of artifacts found within the polygon describing the “hot-spot” of burned material are significantly smaller from the material outside the cluster of burned material (Student’s T: p = <0.001).

3.4.2 Large-Scale Indications of Combustion

The previously described FxJj20Main-Extension-0 was studied as a possible indication of an ephemeral use of fire with rapid occupation. Surface collections from this locality included a small number of artifacts (an ignimbrite bifacially worked chopper and a basalt hammerstone). The basalt hammerstone appears to have typical surface pitting expected from percussive activity, but interestingly also exhibited a *potlid* flake. The hammerstone and flake were recovered approximately 20 cm apart, and within the rubefied, consolidated feature. The FxJj20MExt-0 basalt hammerstone and potlid flake do *not* show "peeling" that is often associated with natural exfoliation of basalt (Figure 22). In addition to the FxJj20MExt-0 feature, surface survey located several other similar (rubefied/baked) features in Area 131.

Photo of recovered artifacts from FxJj 20 Main, Extension 0

Figure 22: (left): Basalt potlid fracture; shows no bulb of percussion or conchoidal curvature. Recovered from FxJj20 MExt-0. (right): Basalt "potlid" re-fit on battered hammerstone. Recovered 20cm apart within rubefied feature at FxJj20Main-Extension-0.

3.4.3 Actualistic Studies

Experimental results reveal that thermal alterations to basalts and ignimbrites from the Turkana Basin correspond to results from previous studies on fire-cracked rock (Purdy and Brooks, 1971; Purdy, 1975). Color, textural and mechanical alterations occur in stone heated in normal campfires. Ignimbrite may explode at medium temperatures (ca. 400°C) while basalt might fracture or spall (only) under higher temperatures (ca. 600°C+). While earlier studies mention color changes (reddening, whitening, blackening) and textural modifications (crazing, pitting, friability) our experiments show these features are not consistently present in all materials exposed to certain temperatures, particularly those of volcanic origin. The experimental heating of knapped lithic materials produced a type of angular fragment that appears indicative of knapped materials that are exposed to high temperatures. We have termed this angular fragment a "thermal curve fracture" or TCF (Cutts et al., 2015).

While preliminary, our interpretation of experimental results indicates a particular heat-expansion pattern occurs on previously knapped materials exposed to temperatures exceeding the 550°C maximum reading as determined by IR thermometer (see Figure 22). Although somewhat similar to the vast majority of angular fragments from archaeological assemblages, closer inspection suggested that these particular fragments—TCFs—are morphologically distinct from unfired debitage. Unworked, raw nodules and cobbles submitted to similar fires did not yield TCFs in any of the experimental fires we conducted. TCFs appear to be produced in basalt when the materials are exposed to high temperatures for a long duration, or are exposed to multiple bouts of high temperatures. For all tested experimental material, TCFs are produced when rocks are exposed to rapidly increasing temperatures (e.g. tossing knapped materials into a high temperature fire). TCFs are regular and scalable; regardless of overall size of TCFs, the proportions of TCFs are more regular than the proportions of unfired knapped debitage. Populations of TCFs are statistically distinguishable from unfired debitage (see Table 8). A comparison between angular fragments produced in the process of normal freehand hard hammer knapping (debitage, $n = 100$) and experimentally derived TCFs ($n = 35$) using multiple measures of width and breadth (10 measurements) identify significant differences between these two populations [Student's t-tests, $\alpha = 0.05$; $p = 0.007$ (width); $p = 0.012$ (breadth)]. These values indicate that curvilinear angular fragments produced through knapping and thermal curved-fractures (TCFs) are distinct.

Table 8: Preliminary results comparing curvilinear fractures from knapped and fired debitage.

Width Comparison	**Thermal Curve Fractures (TCF)**	**Curvilinear Debitage**
Width EQ **Student's *t*-test for width**	1.703 (n = 35)	5.058 (n = 100) $p = 0.007$
Thickness Comparison		
Thickness EQ **Student's *t*-test for thickness**	1.993 (n = 35)	3.759 (n = 100) $p = 0.012$

Evenness of width and thickness calculated by measures at defined intervals across a single object. The deviation of each of these measures from the average measure is used as a measure of evenness across each experimentally derived artifact. Variance is greater across knapped, but not fired, debitage than fragments produced as a result of knapped material that was subsequently exposed to the fire.

Thermal Curve Fractures (TCFs)

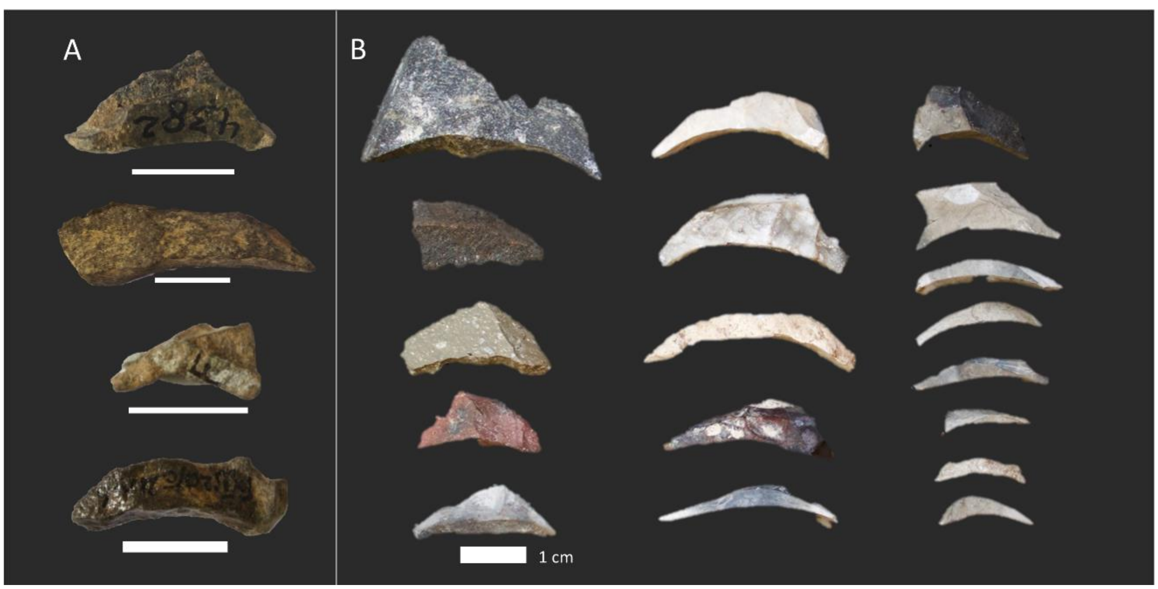

Figure 23: Thermal curved-fractures (TCFs). The potential TCF on top demonstrates statistically similar morphology and was recovered in situ at FxJj20Main during 1970s excavations and labeled "angular fragment" in collections housed at the National Museums of Kenya. On the bottom is an experimentally derived example from a firing event exceeding 550°Celsius. Scale = 1 cm.

A review of angular fragments in the previous collections from the FxJj20 Main sites complex found 15 specimens with a curvilinear shape more similar to experimentally derived TCFs than angular fragments produced by normal knapping processes (see Figure 22).

3.5 Discussion

Although many Early Pleistocene sites preserve striking evidence suggestive of hominin-controlled fire in the Early Pleistocene, very few contain the suite of characteristics that are often used as unequivocal evidence of controlled fire (e.g. hearth features, ash layers, as described in James, 1989). It is imperative, therefore, that paleoanthropologists develop novel, robust techniques to clarify whether the evidence of combustion features recovered from Pleistocene archaeological sites is, in fact, due to hominin activity as opposed to the effects of natural landscape fires.

Despite the challenge of documenting the association of early Pleistocene hominins and fire archaeologically, many paleoanthropologists suggest that the advantages that fire provided for early hominins were so great that there would have been strong selective pressures on these behaviors (Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Wrangham and Carmody, 2010; Gowlett and Wrangham, 2013). A few of the advantages that controlled fire would have provided include: expansion outside of warm lowland areas, extension of the daylight hours allowing for extended social interaction, possible protection from predators, and secondary processing (cooking) of food items that would open up new resources and allow for increased digestion of other resources (Clark and Harris, 1985; James, 1989; Wrangham et al., 1999). Complex behaviors, particularly social mechanisms that have been suggested to be a critical part of our evolutionary success (Dunbar and Shultz 2009), are notoriously difficult to demonstrate archaeologically, so it is unlikely that researchers will be able to determine whether fire was used for warmth, extending daylight hours, or protection from predators. However, cooking food represents a major behavioral shift that may be visible in the fossil record.

To understand these patterns it is imperative that we begin to identify ways in which fire is documented on early archaeological sites. In addition the association of fire and hominin behavior requires us to further explore the nature of archaeological documentation. Patterns that are considered acceptable as evidence at sites from later time periods may be fundamentally different from what we would accept from earlier sites.

Identifying fire in the Early Stone Age: Problems and a Prescription for Future Analyses

It may not be possible to pinpoint the time when our ancestors began to actively produce fire. It is, however, likely possible to identify when hominin behavior becomes associated with pyrotechnology in the archaeological record. A large number of sites with associated fire evidence from similar time periods across a region may provide an indication of when hominin fire use became part of the behavioral repertoire.

Issues with determining the presence of fire in Early Pleistocene sites include problems with identification and recognition of unequivocal evidence of burning events such as ash remnants, burnt bone, and burned stone (Berna and Goldberg, 2007; Berna et al., 2012). The impact of post-depositional processes on these types of evidence over very long periods of time is not well understood. The most common argument used by proponents of a late adoption for hominin use of fire argue that evidence, either in the form of burnt bone or lithics or microscopic evidence of ash or charcoal, is missing from the Early Pleistocene archaeological record.

Direct evidence of fire (ash, charcoal) is ephemeral in nature and easily destroyed (Shahack-Gross et al., 1997; Berna and Goldberg, 2007; Karkanas et al., 2007). Identifying evidence of fire in the Early Pleistocene requires a number of proxies. It is unlikely that any single proxy for ancient combustion will provide the full answers. Furthermore, a reliance on a single proxy is likely to result in a higher likelihood of retaining a false null hypothesis about the origins of fire-use. Many of the features used for the identification of combustion features in the Middle and Upper Paleolithic record do not preserve in many African Early Pleistocene sites because most are open-air locations. It is not possible to identify ash deposits from open-air sites of any great age (Karkanas et al., 2000; Berna and Goldberg, 2007) and even modern ethnographic evidence indicates that hearth features like stone rings are not ubiquitous and ephemeral at best (Binford, 1980, 1983; Brooks and Yellen, 1987; Mallol et al., 2007). In the absence of ash and stone rings in the early archaeological record, we must rely on the association of burned materials and hominin activities as indicated through detailed excavation and fine-grained spatial analysis – methods we have begun to employ at Koobi Fora. The spatial association between well-documented evidence of pyrotechnology and other forms of evidence of hominin behavior is the best possible option for documenting the onset of these behaviors. In particular, evidence for fire-modified archaeological materials is a robust source of data about the behavioral association between hominins and pyrotechnology. If combustion features were proscribed and short-lived, we should expect the evidence to be spatially discrete, while accounting for post-depositional disturbance by animals or root action that could disperse evidence. We do not expect all, or even a majority, of artifacts and bone to be affected by thermal alteration. Rather, like at FxJj20 AB, we expect a limited number of materials to show evidence of thermal alteration, and we expect them to be intermixed with other material, while still preserving some spatial association. Other types of combustion (such as wildfires or lightning strikes) may result in instances of thermal alteration found throughout the spatial and temporal extent of an archaeological horizon. New methods of documenting the association of fire and hominin behavior will require further instances of experimentation to develop hypotheses about the nature of the earliest instances of pyrotechnology. In this paper, we present examples of archaeological data that may provide evidence for the use of fire in the Early Pleistocene that may preserve in some of the earliest archaeological sites.

The search for the earliest evidence of fire will require evidence that is not linked directly to a single site location. The identification of consistent use of combustion by our hominin ancestors is unlikely to be distinguishable from collection of fire from wild sources. It is possible that hominin fire production could have increased landscape fires (Bliege Bird and Bird, 2015), but it is also possible that an increase in landscape fires could have increased opportunities for hominins to collect burning material. These scenarios are likely to be archaeologically indistinguishable. Given this, it is necessary that we begin to investigate the landscape-scale distribution of combustion instances to look at frequency of use, and compare this data to landscape-scale proxies. To accomplish this, we must begin to identify ephemeral instances of fire that appear sporadically across well-preserved landscapes in the past. We expect that sites located in sedimentary contexts of rapid burial by low energy fluvial systems, such as those found in some parts of the Karari Ridge in the Koobi Fora region, will be the most likely to yield this evidence. Areas such as these may have also been ideal for fire use because the resources needed to use fire (e.g. fuel in the form of dried wood) are more likely to be present near permanent sources of water. The identification of relatively small archaeological occurrences associated with combustion features on ancient landscapes may provide the evidence necessary to identify this major transition in human evolution.

Another criticism of the identification of fire in early archaeological sites is that it is difficult to document “regular use” (Shimelmitz et al., 2014). Researchers cite the lack of evidence for fire in cave sites throughout Europe, particularly during glacial maxima, when fire would be the most useful for hominins (Sandgathe et al., 2011; Shimelmitz et al., 2014). In these environments, fire may be a method of thermoregulation that is a necessity in these conditions. One must consider, however, the context in which these occupations took place and issues of preservation related to specific localities. If long-burning fires in East African settings do not create large piles of ash, the signal of those fires is more likely to be lost. European glacial cycles have alternately covered much of the continent with ice or drowned portions of available landmass with sea level rise, both of which may contribute to the loss of data either through erosion of sites or through the destruction of evidence within those sites (Gowlett, 2006). If direct evidence for fire has been obscured through erosion or destruction, then indirect evidence in the form of burned materials may potentially have a greater chance of providing insights into these behaviors.

Techniques for reliably identifying evidence for thermal alteration in bone and sediment have only recently been developed (Shahack-Gross et al., 1997; Berna and Goldberg, 2007; Karkanas et al., 2007), and are only now being incorporated into the study of very ancient fires (Berna et al., 2012; Hlubik et al., 2017a). It may be possible to identify the spatial association between multiple instances of burned bones and hominin technology. A consistent pattern of this association is likely the result of multiple instances of fire production in association with hominin behavior. New methods of spatial analysis, particularly with respect to the location, density, thermal history, and size of materials found on site can be harnessed to identify these patterns. These durable proxies of ancient pyrotechnology, together with spatial analysis, can give us an idea of whether fire evidence and indicators of human behavior can be associated. Inconclusive or negative associations would be more likely indicative of wildfire incidents, while strongly associated evidence would be more likely indicative of purposeful use. To identify these differences, however, we must have a clear understanding of site formation processes, both from a geological and artefactual perspective. Micromorphological geological investigations can give an indication of what specific processes were possible, while artifact orientation and size profile composition can indicate whether the material recovered is close to its primary depositional context.

Previous studies have offered views regarding fire-cracked rock (FCR) and thermally altered stone and soil in archaeological contexts (Purdy and Brooks, 1971; Flenniken and Garrison, 1975; Purdy, 1975; Werts and Jahren, 2007; Mercieca and Hiscock, 2008; Schmidt et al., 2012; Oestmo, 2013). FCR terminology has substantial difficulties with equifinality between the patterns of reddening, blackening, whitening, crazing, cracking, and crenulated surfaces seen in in FCR and other contexts. The TCF morphology is recognizable through a set of quantifiable morphological characteristics. Angular fragments, common in artifact assemblages associated with the manufacture of stone tools, occasionally show clear evidence of flaking, but can lack characteristics of flakes typically allocated as knapping debris, or debitage (Andrefsky, 1986). The majority of angular fragments exhibit certain features that reflect their genesis as byproducts of conchoidal fracturing. Our experimental data, therefore, suggests that this angular fragment portion of many Early Pleistocene assemblages may contain further, previously undocumented, evidence of burning. With the difficulty of identifying thermally altered volcanic raw materials through methods such as FTIR testing, TCFs offer a possibility to identify burned lithics. A larger sample size of experimentally derived TCFs is needed to determine the efficacy of these morphological criteria as an indicator of human-control of fire. TCFs appear to be a method for suggesting the presence of hominin-worked stone in a hot (550°C+), long (2+ hrs.) fire. More experimentation is needed, but the association of these distinctive pieces of stone to fire is certainly intriguing.

3.6 Conclusion

We have presented multiple lines of evidence from new fieldwork and experimentation indicating archaeological remains, associated with materials of the Developed Oldowan or Karari Industry, from the site complex at FxJj20, Koobi Fora, Kenya, show the possibility of human controlled fire:

1. There is a demonstrated association of fired material and artifacts and bone recovered at FxJj20 AB. This association does not prove that hominins were controlling fire, or could make fire, but it provides evidence of the association between fire and hominin behavior in the Early Pleistocene.

2. There is no indication that the site was disturbed to any great extent by post-depositional processes. The micromorphology indicates that the site was buried by low-energy water flow, with subsequent soil formation, but there are no indicators of large bioturbative agents like roots or trees. An analysis of the artifact size profile are consistent with pre-treatment experimental sites from Schick (1986), while orientations are consistent with a random, sloped surface.

3. We have identified several other instances of rubefied sediment on the landscape surrounding the FxJj20 site complex, several of which have artifacts associated on the

surface. Further investigations of these rubefied sediment localities may yield further evidence for fire associated with human activity.

4. We have preliminary data that identifies a distinctive lithic category (TCF) that we have observed to be associated with exposing knapped lithic material to high temperatures. While the mechanics of production are still under investigation, the co-incidence of TCFs and thermal alteration of knapped materials indicates that there may be a connection to these variables.

The investigation of fire in the early archaeological record requires a number of lines of evidence to determine whether fire found on the site might be the result of hominin behavior. Microscopic approaches to the study of fire have proven successful in other contexts (Shahack-Gross et al., 1997, 2014; Rink and Schwarcz, 2005; Berna and Goldberg, 2007; Karkanas et al., 2007; Berna et al., 2012) . We indicate that these techniques show promise in Early Pleistocene contexts. Further, high-resolution excavation of other Early Pleistocene sites is necessary to identify statistically significant clusters of material in combination with materials that are diagnostic of combustion features. Testing of other previously excavated sites from the same time period may be able to identify other instances of fire in the early archaeological record. Sampling of sediment for micromorphological study allows for a careful examination of potential post-depositional processes that include burial, post-burial, and potential issues resulting from diagenesis. FTIR testing of materials from the site, particularly bone and sediment allows for identification of thermally altered materials. Coupled with careful mapping, this allows for the recognition of distinct clusters of materials, which may indicate behaviors of hominins present on the site.

The question of whether and how human ancestors in the Early Pleistocene used pyrotechnology cannot be answered at this time. Based on our present knowledge of these sites within the Koobi Fora Formation we can document the association of combustion and human behavior on at least one site, dated to 1.5 Ma, with the potential of two or more contemporaneous sites within the vicinity of having a similar association. Integrated environmental reconstructions will help inform us about the potential for natural fire in these ecosystems in the past. Further, investigations of fossil wood or deep lake cores may be able to provide information about the nature of natural fire present on the landscape. Evidence for controlled combustion in the Early Pleistocene archaeological record would strengthen the hypothesis that the use of fire, particularly for cooking foods, had a major influence on the biological evolution of the genus *Homo* (Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Wrangham and Carmody, 2010). Previous objections to this hypothesis have cited the lack of evidence for fire in the archaeological record (Roebroeks et al., 2011; Shimelmitz et al., 2014). Yet if evidence for the association of fire and hominin behavior can be shown to be present at Early Pleistocene archaeological sites, then multiple lines of evidence may support this hypothesis.

Chapter 4: Title: Site formation and integrity of FxJj20 AB, Koobi Fora, Kenya and implications for fire in the Early Pleistocene archaeological record

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*Authors: **Sarah Hlubik[1]**, David Braun[2], Francesco Berna[3], Craig Feibel[1], Russel Cutts[4], John WK Harris[1]*

Author affiliations: 1. Rutgers, The State University of New Jersey, New Brunswick, NJ; 2. The Gorge Washington University, Washington, DC; 3. Simon Fraser University, Burnaby, BC, Canada; 4. University of Georgia at Athens, Athens, GA.

4.1 Introduction:

In 1964, Louis Binford suggested that behavior within a site left its own fossil record, which could be discovered by a Holmesian scientist who could decipher the clues. By the mid to late 1970s, some researchers began to question the validity of the assumptions that the patterns found in the archaeological record were solely reflective of the behaviors that created the sites. Schiffer (1972) synthesized some of the biases and inadequacies of the current state of the sciences surrounding the study of site formation processes, and pointed out that behavioral processes are not the only forces to which sites are subjected. Experimental work, from the 1970s through today, in geoarchaeology, taphonomy, and experimental archaeology showed many influences on the archaeological record after initial deposition of the artifacts occurred (e.g.: Schiffer, 1972, 1983, Schick, 1986, 1987; Blumenschine and Marean, 1993; McPherron, 2005; Andrews, 2006; Malinsky-Buller et al., 2011). It is now widely recognized that post-depositional processes are critical to the interpretation of archaeological sites. While behaviors certainly lead to discernable patterns, those patterns cannot be considered valid unless one can discuss how the site has been affected after creation by the movement of water or animals across it, compaction or slumping of sediments, erosion, or growth of plants.

An understanding of the post-depositional processes and their potential effects on the archaeological record is critical to an accurate interpretation of archaeological sites. The effects of anthropogenic, geological, chemical, and physical processes on the location and preservation of artifacts and ecofacts determine the formation of the site as it is excavated. Thus, an understanding of how these processes have co-affected a site will give researchers greater insight into the original context of the site (Schiffer, 1983; Courty et al., 1989; Stein, 2001; Mallol et al., 2007). Site formation studies have spanned research that concentrates on the behavioral origin of sites to the geological influences that have affected materials after they have been deposited (Stein, 2001), but it is most critical to combine these approaches through multi-proxy analysis to be able to say much about the formation and depositional history of a site. Spatial analysis of the materials found within a site give insight into the behaviors that created them, but without an understanding of the syn- and post-depositional processes (burial, erosion, bioturbation) the validity of any spatial analysis can be called into question. Water action can create false associations between material, especially if there is a large immovable object like a tree in the path of the water (Schick, 1986). Bioturbation of large rodents or large roots can push objects out of place, removing them from a site or pushing them into underlying layers (Stein, 2001). These processes must be fully understood before any statements about spatial associations of archaeological materials can be taken seriously.

Schick (1986) conducted a seminal study on the effect of water movement of the formation and preservation of materials from a site. The experiments documented the effect of water movement on spatial patterns and artifact size profiles from known production sites and demonstrated that patterns can be disturbed or created by mid- to high- energy water movement (Schick, 1986). She documented how large rocks or trees could influence redeposition patterns, particularly of smaller (=<2cm) artifacts, and showed that looking at the profile of sizes recovered and refitting pieces of the material could distinguish between production sites and those disturbed by water (Schick, 1986).

Orientation analysis (McPherron, 2005, 2017) can offer insight into the effect of water movement or geological processes such as slumping on a site. These analyses can identify whether significant movement after the deposition of archaeological material has influenced what the archaeologist has found by showing whether material is randomly oriented throughout the site or follows some axis of movement through a process like water movement or geological slumping (McPherron, 2005, 2017). A random, planar orientation on a site would indicate that no significant post-depositional movement has occurred on the site (McPherron, 2005, 2017). However, compaction of sediments may also lead to orientation changes in artifacts (Andrews, 2006). Andrews (2006) found that nearly all artifacts from experimental sites that were not flat or vertical in the beginning changed orientation with the increase of pressure on sediments. This experiment also showed that increases in pressure also resulted in downward displacement of artifacts, mimicking the movements of sediments themselves (Andrews, 2006).

Soil micromorphology can help to tease out some of the geological, pedologic, diagenetic, and bioturbative influences on a site (e.g.: Karkanas et al., 2000, 2007; Kooistra and Kooistra, 2003; Goldberg and Berna, 2010; Mentzer, 2014; Shahack-Gross et al., 2014). Using petrographic thin-sections of intact archaeological deposits, microscopic evidence for soil formation, compaction, animal burrows, root action, and chemical changes that could influence the final organization of a site can be retrieved (Kooistra and Tovey, 1994; Kooistra and Kooistra, 2003; Goldberg and Macphail, 2006). We can use soil micromorphology to assess the degree of root action visible and to detect the amount of sediment compaction by looking for evidence of collapsed or compressed root canals (Kooistra and Tovey, 1994).

In the case of FxJj20 AB, there is evidence for the association of fire and hominin activities (Hlubik et al., 2017, in review.), but a more in-depth look at the processes which affect site formation is necessary to determine whether that association is the result of hominin activities or the accidental association of natural fire with hominin activities after hominins had left the area. In this paper, we discuss the orientation of recovered materials from FxJj20 AB, Koobi Fora, Northern Kenya, in light of micromorphological findings from the site, to determine whether the archaeological materials are in primary context, or whether significant post-depositional processes have affected the placement of materials. We then discuss this in context of the spatial distribution of materials found on site to determine whether post-depositional process may have affected where materials are found on site.

4.2 Background to the study

The site of FxJj20 AB is located in the Karari region of the Koobi Fora paleontological region of Sibiloi National Park, in Northern Kenya, along the shores of Lake Turkana (Figure 24). Koobi Fora is rich in both human paleontological and archaeological sites that date back as far as the Pliocene, and archaeological sites that date back to the Early Pleistocene. FxJj20 AB is located approximately 150 m northeast of sites FxJj20 East and FxJj20 Main and is overlain by the Morutut Tuff, dated to 1.6 mya (Brown et al., 2006). It is located in tuffaceous silts overlying a heavily carbonate concreted zone and is overlain by more tuffaceous sandy silts (Harris, 1997). These sandy silts likely represent the onset of floodplain deposits, though the exact location of the channel in this area is unknown (Harris, 1997). The site was originally discovered in the early 1970s, when a test excavation was undertaken, and subsequently reopened and expanded to the east and north in 2010; excavations have been ongoing since the site was reopened. The FxJj20 East and FxJj20 Main sites were the first sites proposed as Early Pleistocene fire sites in the early to mid-1980s (Clark and Harris, 1985) because of consolidated patches of rubefied sediments found in and among the artifacts there. Subsequent geophysical work identified these patches as potential fire loci, and postulated that the sites may represent the earliest archaeological evidence for fire use in the record (Clark and Harris, 1985; Bellomo, 1994a; Bellomo and Kean, 1997; Rowlett, 2000). No rubefied patches were identified at FxJj20 AB, but the original excavation notes discuss the presence of smaller rubefied clasts of sediment in the sieve. The presence of these rubefied clasts, along with the high density of material recovered in the northeast corner of the original excavation, indicating that the deposits likely continued, prompted the reopening of the site. The original excavation at FxJj20 AB opened up 16 m^2, and found a dense concentration of materials in the northeastern portion of the excavation, with less dense concentrations to the south and west. In 2010, we returned to the site to reinvestigate and opened a further 22 m^2 to the north and east of the original excavation (Figure 24).

Location of FxJj20 AB

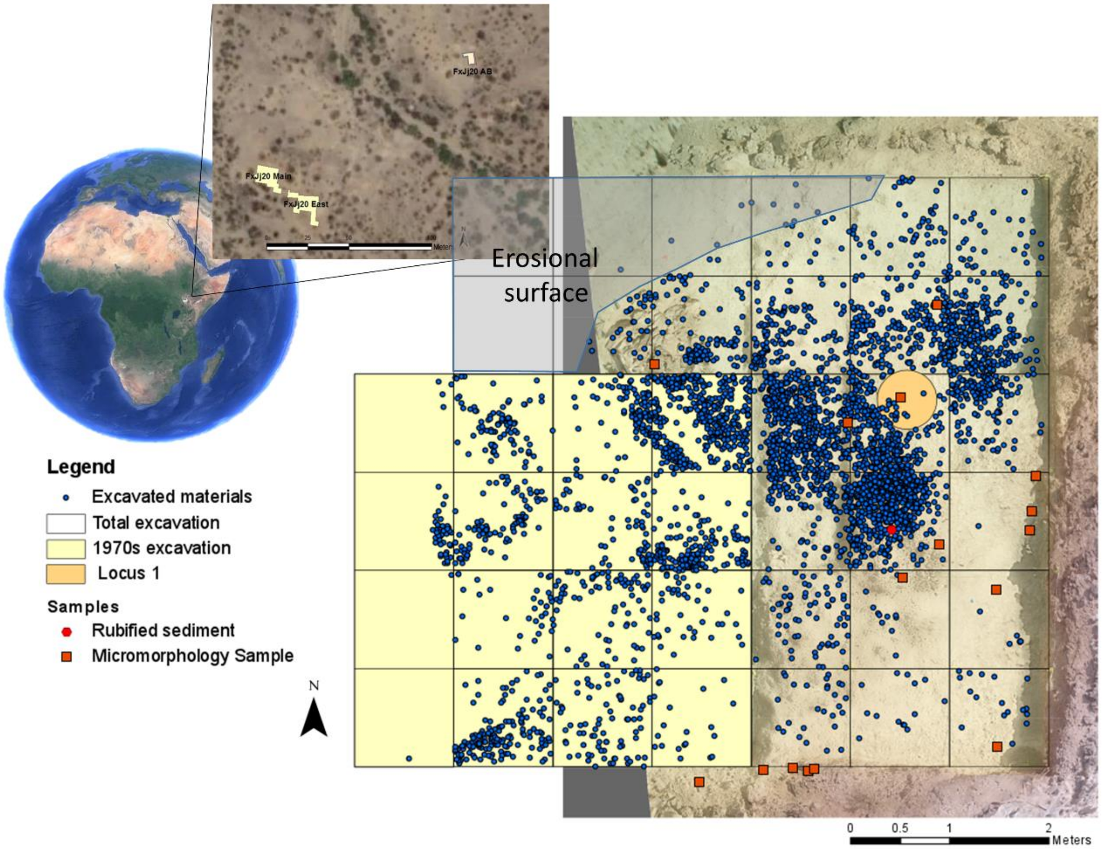

Figure 24: Map showing location of FxJj20 AB and detail of excavation

The recovered archeological materials are primarily animal bone fragments and lithic material from knapping activities. Many of the recovered lithic artifacts can be classed as debitage: either split or snapped flakes or angular fragments (detached pieces with clear evidence of having been produced but lacking a platform or bulb of percussion). Most of the lithic raw material recovered is basalt, though a small portion has been identified as ignimbrite, chert, quartzite, or chalcedony. Faunal analysis of the materials recovered from the site is ongoing, as much of the material is highly fragmentary, but preliminary analysis shows the presence of fish, mammals (bovids and suids), and reptiles. There is a dense concentration of materials found roughly in the center of the excavated area (Figure 24) and much of the bone fragments from this area has been tested for burning by Fourier Transform Infrared spectroscopy (FTIR), with 40 bones in the cluster being identified as burned (Hlubik et al. 2017). Lithic analysis revealed the presence of potlid fractures on some of the lithic artifacts recovered from the site and spatial analysis of burned bone and stone indicated that burned materials are associated with hominin occupation of the site. These materials are distributed throughout the high-density cluster both horizontally and vertically (Hlubik et al., 2017a).

4.3 Methods

New excavations at FxJj20 AB are undertaken using small tools to allow for the recovery of artifacts and bone fragments as small as 2-5mm and the recording their three-dimensional spatial coordinates. Removed sediment is screened through 2mm mesh, and all materials recovered in the excavation are recorded using a high precision Leica Total station and handheld data recorder using EDM Mobile, developed by Shannon McPherron and Harold Dibble (McPherron and Dibble, 2011). Intact sediment blocks for Soil micromorphology were sampled according to standardized protocols (Goldberg and Macphail, 2006; Goldberg and Berna, 2010), and shipped to the USA for analysis after petrographic thin-section preparation. The samples for soil micromorphology were taken throughout and above the archaeological horizon, as well as in areas without lithic artifacts and fauna at a similar stratigraphic height and in similar sediments. Figure 25 shows the location of the thin sections taken from the site. The petrographic thin sections were described using a petrographic microscope according to Stoops (2003) and analyzed at the Geoarchaeology Laboratory at Simon Fraser University, in Burnaby, Canada.

Photograph of FxJj20 AB with sample locations

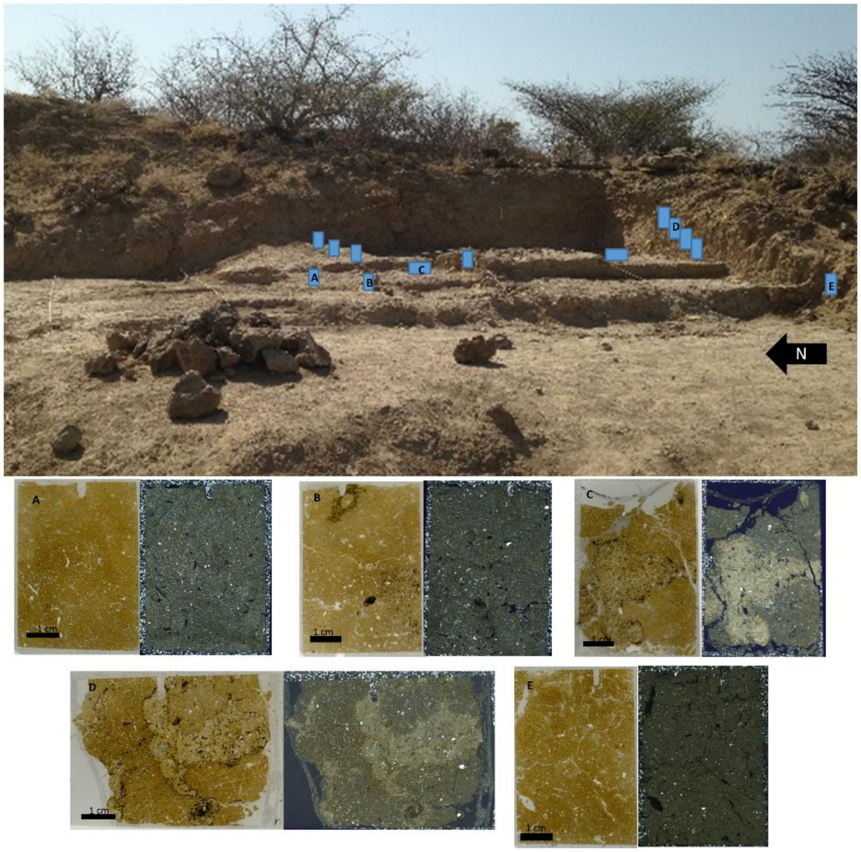

Figure 25: Photograph of FxJj20 AB with locations of all micromorphology samples from the site imposed. The lettered samples correspond with the thin sections scans below the photograph.

For archaeological materials with one axis longer than the other, two sets of spatial coordinates were shot in with a total station at either end of the long axis to measure its orientation, bearing and plunge. Orientation analysis was conducted using NewPlot (McPherron and Dibble, 2010) and the R Script developed by Shannon McPherron (2017). These analyses calculate bearing and plunge of elongated objects to generate Rose diagrams and determine whether the materials exhibit a preferred orientation. A preferred orientation would indicate post-depositional disturbance by water or geological activity (McPherron, 2005, 2017). Eigenvalues generated from bearing and plunge are used to place the orientation data into Benn space and the R script is used to resample materials and determine 95% confidence intervals for the placement of materials in Benn space (McPherron, 2017). Benn space is useful in distinguishing between types of fabric orientation by plotting eigenvalues in a ternary diagram representing planar, isotropic and linear orientations (Benn, 1994). Planar fabric orientations with no preferred bearing or plunge are considered random and would be expected for a site in primary context (McPherron, 2005, 2017) This has been used a number of times to assess experimental and archaeological collections (Lenoble and Bertran, 2004; McPherron, 2005, 2017).

4.4 Results

4.4.1 Soil Micromorphology

The archaeological horizon at FxJj20 AB is found in a massive mudstone bed, dominated by silts with tuff mixed in, showing amorphous cross-sectional geology (Kaufulu, 1987). The depositional environment is classified as being a distal floodplain with low depositional energy that has been reworked by vegetation growth, burrowing, and even trampling (Kaufulu, 1987). No visible evidence for large-scale bioturbation was observed during the excavations; larger burrows or root tunnels should be visible on a larger scale, but none of these have been observed during the excavations. The micromorphology supports this, indicating a rapidly aggrading surface with incipient soil formation, but no long-term stable surface. Particle size is small, primarily silt-sized, with some clay particles, tuff, and small amounts of fine-grained sand. There are no visible paleosurfaces within the thin section blocks, but there is clear reworking of sediments that were likely at the surface prior to burial. Sediments are fine-grained (silts and tuff) and indicate low-energy water burial (Hlubik et al., 2017a). After the deposition of the sediments, soil formation occurred. No stable paleosol horizon is observed within the stratigraphic section, but the extensive reworking of sediments throughout the column indicates that any A-horizon might have been lost through the process of sedimentation and reworking of the materials through insect and root action. The thin-sections show the formation of a stable B-horizon with abundant small passage features. Figure 25 shows that materials throughout the site are similar in appearance, sedimentological make-up, and similarly affected by small root or insect burrows, indicating that the entire site was affected by similar processes, and show no evidence for small size vertebrate or large root burrows (Hlubik, et al 2017).

Clay crusts, which form in puddles, are found throughout the thin sections. These crusts are reworked in the sections, likely the result of the small-scale bioturbation caused by vegetation and insect action. The passage features created by this bioturbation have evident clay coatings (Figure 26), which are generally thin and usually line both sides of the passage features, but do not infill them completely. These crusts and coatings are evidence that water was abundant in the system when the site was being buried and for a period after that. The passage features on which clay coatings are found are located throughout the thin sections, particularly those found within and below the archaeological horizon. Clay coatings are less abundant in the thin sections found higher in the stratigraphic section of the site. The water content of the sediments at that time the site was deposited and buried was much higher than the present, though at some time after site burial, the area began to dry out and carbonate nodules began to form above and at the archaeological level (Figure 25, *C &D)*. The carbonate nodules at the archaeological level are concentrated in the southern portion of the exposed site, and are generally found above the archaeological level in the northern portion of the site. The vertical distribution of artifacts indicates a gentle slope (Hlubik et al., 2017a), so the disparity in carbonate nodules may be indicative of past surface topography.). A general sequence of sedimentological events can be discerned from the micromorphology. Fluvial deposition of fine-grained tuffaceous silts was followed by extensive small-scale bioturbation. Fluvial deposition of materials likely continued for some time, as indicated by the presence of clay crusts and clay coatings. Between episodes of flooding, the location likely drained sufficiently to allow for the growth of small plants, like grasses, as indicated by the abundant passage features. Sometime after the deposition and burial of the site, the area became more arid as indicated by the formation of carbonate nodules within the stratigraphic column.

Clay Coatings and Clay Crusts from FxJj20 AB

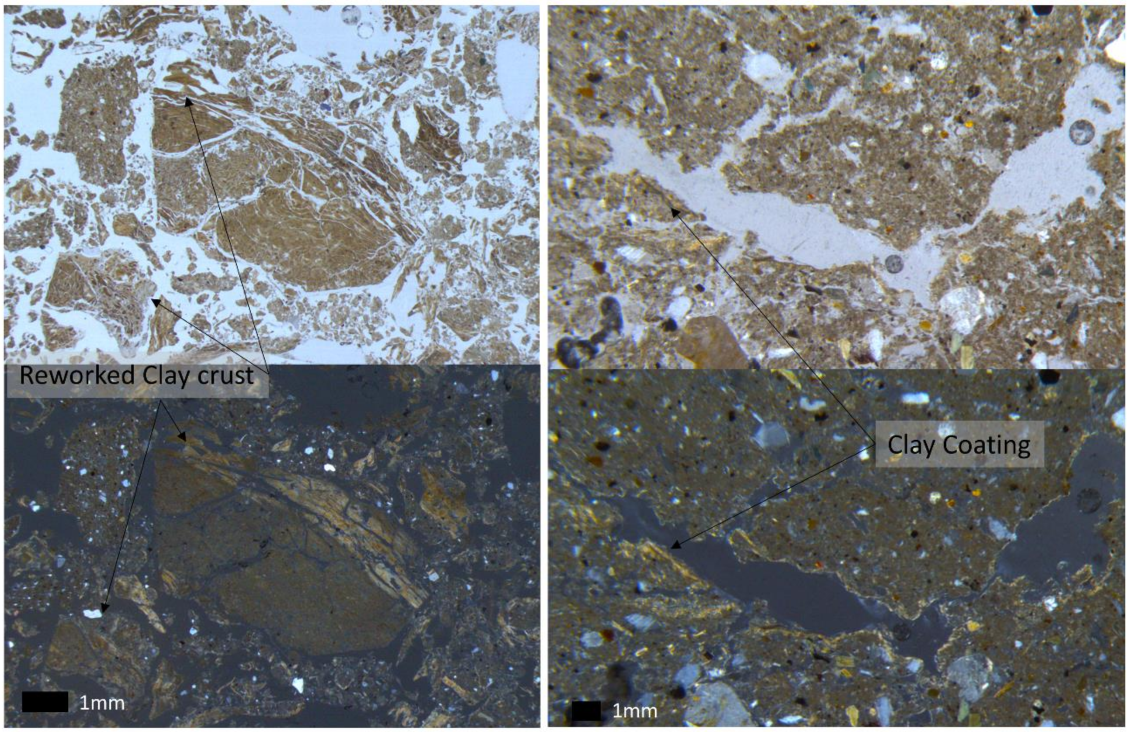

Figure 26: Magnified scans in plain polarized (top) and cross-polarized (bottom) light. Image on the left depicts reworked clay crusts from the thin sections. On the right is a close-up of the clay crusts common throughout the site.

Reworked sediments, primarily clay crusts (Figure 26) indicate the former location of surfaces where water puddled. None of these is particularly extensive through the thin sections, but show signs of being reworked, likely the result of root action which mixed the sediments throughout the column. This root action is also likely responsible, at least partly, for the vertical dispersion of artifacts through the site. A limited number of experimental studies have been conducted on the causes of vertical dispersion in archaeological layers, and these have mostly looked at the effect of soil compaction and shrinking and swelling of clay on the dispersion and orientation of artifacts (Courty et al., 1989; Andrews, 2006).

The sediment from the site does not appear overly compacted. We can see a number of voids, some as long as a few centimeters, through thin sections; these voids can be traced by following clay coatings that generally line the sides. Had the sediments compacted after the formation of the clay coatings, we would expect to see evidence of pinched or discontinuous voids, possibly with evidence of clay coating fragments included in the ground mass. Evidence for passage thinning or pinching is not observed in the thin sections. The vertical spread of artifacts (Figure 27) supports a lack of collapse or compaction in the sediments, as there appears to be more upward displacement of the artifacts through the column. With compaction, such as from trampling, we would expect to less spread of the archaeological material vertically, particularly on fine-grained sediments (Gifford-Gonzalez et al., 1985). Figure 27a shows the vertical spread of the materials from the site. One can follow a horizon beginning at ~10 cm in height in the west to up to ~40 cm in height in the east. To the east, particularly, from where many of the artifacts are recovered, there is a greater dispersion upward of this line. Materials observed below this line were recovered in the far north of the site where modern erosion may have moved some material.

Vertical distributions of materials from FxJj20 AB

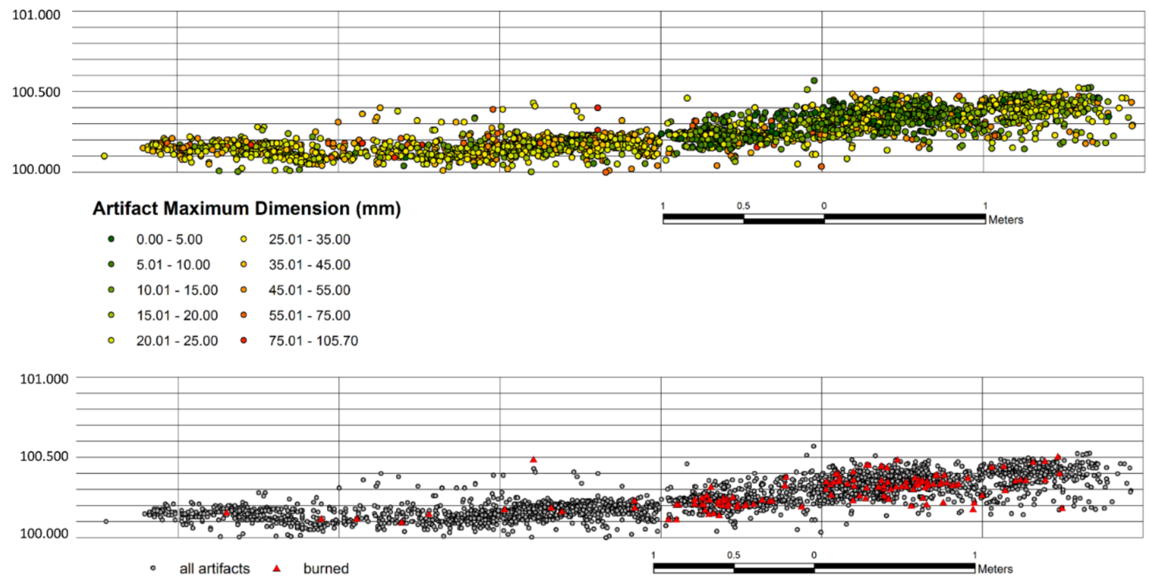

Figure 27: Vertical spread of materials from FxJj20 AB. Top shows the materials broken down into size categories. Bottom shows the location of burned material (red) throughout the archaeological layer

The dispersion of materials through the vertical section shows a thorough mixing of burned and unburned material throughout the archaeological horizon (Figure 27b). The mixing, both horizontally and vertically, indicates that the burned material is not likely the result of a post-burial burn with subsurface heating (Aldeias et al., 2016). In such a case, we would expect to see a more concentrated incidence of burned material vertically, and at a higher level in the stratigraphic column, not mixed throughout the section.

4.4.2 Orientation Analysis

The orientation data shows no preferred directional orientation of the elongated materials (n= 108, Figure 28), indicating that the materials have not been affected by directional water movement. The measurements of elongated materials are only available for the 2010 and later excavations. In Benn space, these materials plot in the planar corner of the triangle and 95% confidence intervals, calculated from resampling the collection 10,000 times, confirm a planar organization of the materials. Most materials shot with two-shot data are larger than 2 cm in maximum dimension (average = 39.67 mm, n= 96). The rose diagram shows that the materials are randomly arranged, and the plunge for most materials is close to 0º, primarily between 0 and 10 degrees (Figure 28). The planar organization of these materials indicates that the archaeological materials were laid down on a relatively flat surface, while the orientation analysis shows that reorganization by water is not likely.

Orientation Analysis of FxJj20 AB

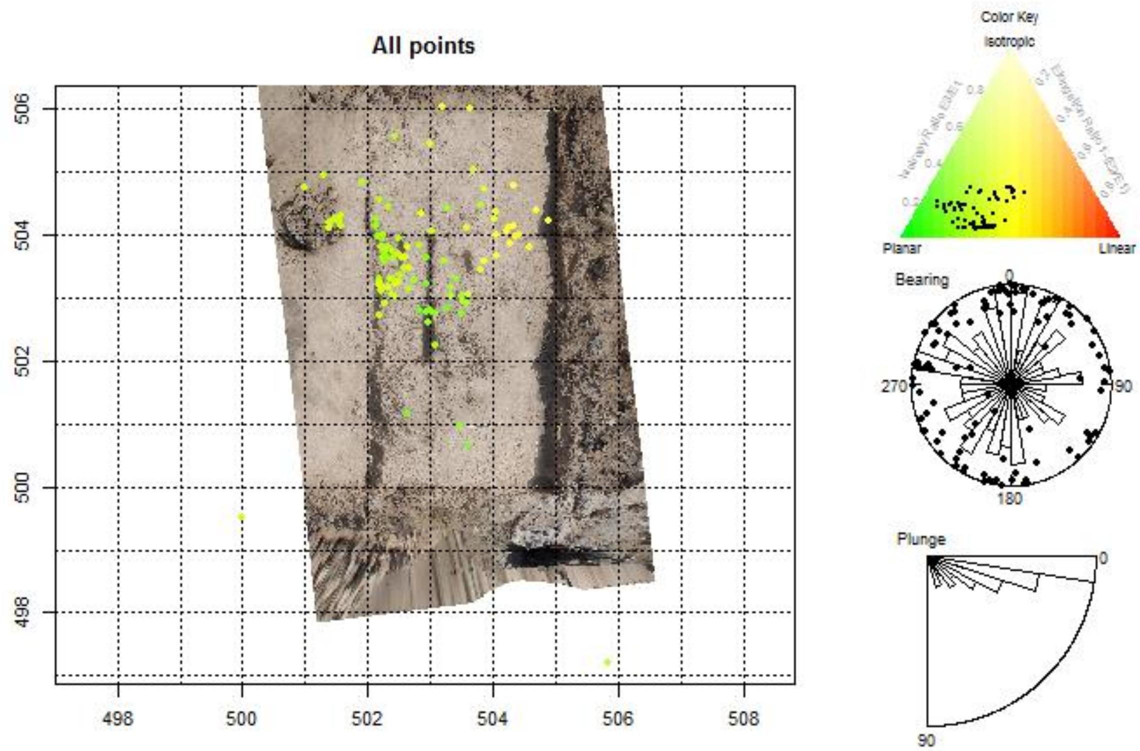

Figure 28: map showing the location of all two-shot data. Color coding in plot shows where in Benn space each item would plot. Benn space diagram (upper right) shows that the material from the site plots at the planar end of the diagram. Rose diagram shows no preferred orientation of the materials. Most materials have an observed plunge between 0 and 10 degrees.

4.5 Discussion

The fine-grained sediments from the site show that low-energy water was responsible for burying the site, while the orientation data shows that this water was not responsible for reorganizing the site itself. Despite the extensive small-scale bioturbation observed in the thin sections, there is no evidence that major bioturbative processes have affected the archaeological material, nor do the sediments show evidence of post depositional compaction. These data indicate that the site is substantially in primary context, which, in turn, supports the hypothesis that associations indicated by the spatial analysis of the site are valid.

Spatial analysis of the archaeological material, coupled with FTIR analysis of bones and sediment indicate the presence of fire associated with hominin activity (Hlubik et al., 2017). The results of the current study indicate that this association is valid and that water movement and major post-depositional processes have only partially affected the original context of the materials found on the site. The vertical spread of the materials (discussed in detail in Hlubik et al., 2017, in press) is considerable, but as the micromorphology indicates rapidly aggrading sediment subsequently affected by small root action, this spread may be the result of upward movement of materials as small roots move materials through the column. The spread at FxJj20 AB is similar to the spread at FxJj50, where refit studies have shown that the spread observed there does not preclude the material being from one archaeological level (Bunn et al., 1980). There is little evidence for soil compaction in the micromorphology and this is supported by the vertical spread of materials upward from a line that can be followed at the base of the artifact-bearing layer. This spread may be caused by root action of small plants, such as grasses, which have tightly clustered roots systems that can mix and rework the sediments through which they grow. Small rodent bones are found throughout the site, despite the lack of evidence for burrows in the thin sections, and the action of these rodents may also be partially responsible for vertical dispersion of artifacts throughout the site.

The research at FxJj20 AB confirms the possibility to find sites retaining a sufficient amount of integrity to make determinations about behaviors of hominins. In the case of FxJj20 AB, the behaviors observed include the burning of animal bone and sediment. The burned materials are mixed throughout the archaeological layer. This indicates that the burning took place while the material was exposed, either at the time that hominins utilized the site, or just prior to burial, since the burned materials were exposed to the same post-depositional processes as the rest of the archaeological materials.

4.6 Conclusion

The data presented here do not indicate major disturbances on the site and support the hypothesis that the site is in primary context and that spatial relationships seen on the site are valid and reflective of the relationships as they existed at the time the site was buried. The site shows evidence of post-depositional disturbance by small root action, but no discernable evidence that major movement by water, roots, or animals changed the layout of the artifacts after burial. This leads us to believe that the site is in its original context and that the associations noted in the spatial analyses are valid. In the greater context of the significance of the site to the study of fire, this means that evidence for fire in the form of burned bone and sediment, is likely evidence of hominin fire use, and not of accidental associations created by post-depositional processes like water movement. In light of this, we suggest that the site is in primary context and minimally disturbed by outside influences, meaning that the associations of fire and hominin behavior that we find on the site are real associations between fire and behavior. This does not mean that hominins at FxJj20 AB were creating fire, but there is good reason to believe that they were using fire in the Early Pleistocene.

Chapter 5: Conclusion to the Dissertation

5.1 Conclusions of the research

Dated to 1.6 mya, the FxJj20 AB site is one of the earliest sites with evidence for fire use in the hominin record. The site appears to be in primary depositional context, which supports the hypothesis that any spatial relationships seen on the site are real. The spatial relationships determined through hot spot cluster analysis support the idea that human ancestors on the site were using fire in the Karari region of Koobi Fora during the Early Pleistocene.

The site exhibits no evidence for major disturbances. Following is a list of evidence presented through the three papers that support this claim.

1. Evidence for major water disturbance is lacking. Sediments on the site are fine grained and homogenous. Orientation analysis supports the hypothesis that the artifacts are randomly oriented on a relatively flat surface, and show no indication of movement through the site. The size profile of the material from the site and the experimental materials is also similar. The proportion of debitage recovered from the site is very similar to the proportion of debitage produced during experimental work by Schick (1986).
2. The evidence for major post-depositional bioturbation is lacking. There is no evidence for large root canals or rodent burrows. The evidence available indicates that the area was subject to frequent flooding events that would have brought new sediment in burying whatever was on the surface. After the area dried out, grasses would grow until the next inundation and burial. The action of the grass roots is a likely culprit for the vertical movement of materials through the archaeological layer.

3. Spatial analysis of materials from the site show a high density of materials in the center of the site, made primarily of small (=<20 mm), which is consistent with Binford's (1980, 1983) Toss and Drop Zones and the McKellar pattern (Mckellar, 1973). With the orientation and the size-profile data, this indicates that we may be able to discern more about individual activity areas within the archaeological layer. Because excavations and analyses are continuing, it would be unwise to say that we might be able to correctly interpret the behaviors recorded at the site at this time. However, it does appear from the recovered materials that we can discern a production area where a large proportion of small debitage has been recovered.
4. Beyond artifact production behaviors, spatial analysis has also been shown that evidence for fire is not likely the result of a wildfire event. Evidence for fire is present in the form of burned bone and burned sediment. This material is mixed throughout the archaeological layers and is not clustered vertically, though horizontally, there appears to be a hot-spot cluster in the area of highest artifact density. This indicates that the fire was locally concentrated (i.e. not a diffuse source such as a wildfire) and that materials were affect at or around the time of site creation, since they were subject to the same post-depositional mixing as the rest of the archaeological materials.
5. The co-occurrence of fire evidence and archaeological evidence presents a strong argument for the occurrence of controlled fire on FxJj20 AB. This is currently the oldest archaeological site with evidence for fire and human activities and has major implications for the influence of fire on the biological and cultural evolution of humans.

The research conducted for this dissertation has shown that meticulous excavation of materials using small tools with a goal of recovering as many small pieces with provenience data can be successful at detecting fire in the ancient archaeological record at open-air sites. This is critical to the research into early fire, as many very early archaeological sites are open-air sites, and fire evidence tends to be ephemeral in nature and subject to destruction. This research shows the importance of multidisciplinary approaches to the study of ancient behaviors and begins to suggest future avenues for study.

5.2 Future work

The future of this research lies in incorporating more fields of investigation into fire. Microarchaeological techniques to look at other microscopic residues from charcoal and plant materials may prove to be another option for investigating fire in the archaeological record. This technique has been used at sites from later time periods in Europe (Cabanes et al., 2010; Katz et al., 2010) and to look at microscopic plant materials from sites of similar ages (Albert et al., 2006; Bamford et al., 2006). The presence of microscopic charcoal would indicate the presence of fire in the archaeological record, but it is unclear whether it is reflective of general environmental conditions or specific conditions of concentrated fire occurrences. More experimental work needs to be done in this are to determine the role of microcharcoal in the archaeological record. Phytolith studies may be able to identify the specific and general plant communities of the region. Grasses produce a large number of phytoliths in comparison to other plants in the environment. If grasses are present in an environment, we should expect to see a high proportion of them in samples. If samples from areas within a grassy biome have a high number of woody phytoliths, this should reflect a real concentration of woody materials, not simply a single tree or bush that was present. We would expect fire loci to have a high diversity of phytoliths including many grasses and some woody phytoliths.

In the coming years, I will use a novel combination of experimentation, archaeological fieldwork, and micro-archaeological approaches to studying the advent of hominin control of fire at Koobi Fora, Kenya. Building from the work presented here, this project incorporate new methods and apply several micro- and macro- archaeological techniques new sites discovered in the field and to collections housed at the National Museums of Kenya, in Nairobi. The long-term goal is to survey sites from the Okote Member of The Koobi Fora Region, compare these results between subregions of the basin, and then expand the search to the earlier KBS and later Chari members. Evidence in the form of burned bone or sediment from previously excavated collections will be combined with all data gathered from future site excavations to develop a database for the fire presence in archaeological contexts, and when that evidence begins to appear with frequency.

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