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Hominin fire use in the Okote member at Koobi Fora, Kenya: New evidence for the old debate

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ABSTRACT

Hominin fire use in the early Pleistocene has been debated since the early 1970s when consolidated reddened sediment patches were identified at FxJj20 East and Main, Koobi Fora, Kenya. Since then, researchers have argued for evidence of early Pleistocene fire use at a handful of archaeological sites with evidence of combustion. Some argue that morphological evidence of early *Homo erectus* fossils indicates a dietary shift to higher quality food sources, which could be achieved by cooking. Others contend that fire use does not become a regular behavior until later, in the middle Pleistocene, when archaeological sites begin to show regular evidence for fire use. An early date for hominin control of fire would help to explain the grade changes seen with the appearance of *H. erectus*, while a later date would mean that fire would have had little influence on the early development of the lineage. Early hominins would have encountered fire regularly on the landscape, increasing the possibility of hominins interacting with and habituating to natural landscape fire. Only a detailed understanding of the patterns of controlled and natural fires can lead to understanding of early hominin fire use. We present new work on the evidence of fire at the FxJj20 Site complex in Koobi Fora, dated to 1.5 Ma. We highlight evidence of burning found on site through Fourier Transform Infrared spectrometry, and describe ongoing work to investigate the association of hominin behavior and fire evidence. We present data supporting the hypothesis that the site is undisturbed and discuss spatial relationships showing burned material associated with non-burned material. We present data on a type of stone fragment, the Thermal Curve Fragment (TCF), which is indicative of knapped material being exposed to high heat. Finally, we suggest future directions on the topic of fire in the early Pleistocene.

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 morphology of Pleistocene hominins, including *Homo erectus* (with its larger body size, relatively smaller teeth and probably less complex gut (Walker and Leakey, 1993; Aiello and Wheeler, 1995; Aiello and Key, 2002; Aiello and Wells, 2002; Evans et al., 2016), suggests to some researchers that hominins had controlled use of fire for cooking (Wrangham et al., 1999; Wrangham and Conklin-Brittain, 2003; Carmody and Wrangham, 2009; Wrangham, 2009, 2017; Wrangham and Carmody, 2010; Carmody et al., 2011). Others have suggested that fire was a prerequisite for the consistent habitation of environments outside equatorial and tropical regions (Gowlett, 2006; Gowlett and Wrangham, 2013). Landscape wildfire may have been a viable source of fire for hominins in adapting to combustion before incorporating it regularly into their behavior (Parker et al., 2016), as modern savannah chimps are able to navigate landscapes that frequently burn safely, and are familiar with the mechanics of fire sweeping over the landscape (Pruetz and LaDuke, 2010; Pruetz and

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Herzog, 2017). Familiarity with landscape fire has been hypothesized as an avenue for ancient hominins to adjust to and incorporate fire into their behavioral repertoire without the use of technology to start fires (Parker et al., 2016). Glikson (2013) suggests that the control of fire in the early Pleistocene is tied to widespread environmental manipulation. In this scenario, hominins using fire may be architects of landscape change and grassland maintenance (Glikson, 2013) and key actors in the stabilization of the savanna biome in East Africa. Fossil wood studies indicate an increase in fire prevalence on the landscape beginning around 1.9 Ma in the Omo region (Dechamps, 1984), which may provide support for the argument that fire influenced the physiognomy of ancient savanna environments (Bliege Bird and Bird, 2015).

The advent of pyrotechnical skill in hominins has been proposed by some to begin 1.7–1.5 Ma (Wrangham, 2017). 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 securely dated to 1.5 Ma (Harris, 1977, 1998; Clark and Harris, 1985; Barbetti, 1986; Bellomo, 1994a) represented a major piece of initial evidence in this debate. Paleomagnetic testing and phytolith analysis of the rubefied patches suggested the presence of combustion, although the evidence was equivocal as the patterns observed were generally similar to controlled experimental fires, yet some experimentally burned tree stumps displayed similar patterns (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, 2011a, b). Many Paleolithic archaeologists remain skeptical about the early origins of pyrotechnology (James, 1989; Sandgathe et al., 2011; Roebroeks and Villa, 2011a,b; Sandgathe, 2017; Sandgathe and Berna, 2017). 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 until at least 0.5 Ma (see Clark and Harris, 1985; James, 1989; Alperson-Afil and Goren-Inbar, 2010; Goldberg et al., 2010, 2017; Roebroeks and Villa, 2011a, b; Sandgathe et al., 2011; Roebroeks and Villa, 2011b; Shimelmitz et al., 2014; Sandgathe, 2017 for a complete review of the debate).

Several studies have put forward evidence for fire at early/early middle Pleistocene sites in eastern and southern Africa and southwest Asia (Table 1) (Harris, 1973, 1997, 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; Brain, 1989; James, 1989; Bellomo and Kean, 1997; de la Torre, 2011; Berna et al., 2012). Evidence of combustion at these sites is relatively uncontroversial. However, the ability to discern, or even infer, the anthropogenic nature of these materials as opposed to attributing it to natural events has long been a matter of debate (James, 1989; Sandgathe et al., 2011; Shimelmitz et al., 2014; Sandgathe, 2017). There is currently no consensus on the source of the combustion. Archaeologists use various lines of evidence to support human control of fire, including hearth features and ash layers (sensu James, 1989), 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). Very few of the early Pleistocene sites with evidence for combustion contain the suite of characteristics that are often deemed as diagnostic evidence of controlled fire. It is thus imperative that paleoanthropologists develop novel, robust techniques to clarify whether the evidence of combustion features recovered from early Pleistocene archaeological sites is, in fact, due to hominin activity as opposed to the effects of natural landscape fires.

Researchers investigating the presence of fire in the early archaeological record encounter several difficulties in resolving the question of how and when fire became part of our ancestors' behavioral repertoire. First, many of the earliest archaeological sites come from open-air contexts with substantial post-depositional modification (Gowlett et al., 1981; Isaac, 1982; Stahl et al., 1984; Barbetti, 1986; James, 1989; Goldberg et al., 2017; Sandgathe and Berna, 2017). Evidence of fires can be scattered or destroyed even in relatively undisturbed contexts in open air settings. Disturbed sites may result in false associations between combustion and hominin behavior (Berna and Goldberg, 2007; Goldberg et al., 2017). Moreover, the presence of landscape wildfire may also mimic the signal of anthropogenic fire on a site, particularly if vegetation around a site is patchy and discontinuous (Aldeias et al., 2016; Goldberg et al., 2017). Disentangling the signals of natural and anthropogenic combustion requires a multi-step process that evaluates the presence of fire in the record alongside the association of combustion proxies and specific traces of hominin behavior (Barbetti, 1986). In this paper, we will review the evidence for fire in the early Pleistocene archaeological record of Koobi Fora, and present new evidence for an association between combustion features and hominin behavior 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.

Table 1
Table of sites showing evidence for early fire in Africa and Israel. These sites show evidence for fire associated with hominin occupations in the Early Pleistocene and Early middle Pleistocene.[a]

Site	Date (Ma)	Evidence
Gadeb, Ethiopia[1,2,5]	1.45–0.7	Discolored ignimbrite artifacts with thermoremnant magnetism (TRM) consistent with being heated
Middle Awash, Ethiopia[1,2,5]	>0.6	Circular discolored sediments
Koobi Fora, Kenya[5]	1.5	Circular, discolored sediments, Thermoluminescent and paleomagnetic results consistent with burning, spatial association of artifacts with burned patches
Swartkrans, South Africa[5,6,7]	1.2	Burned bones
Chesowanja, Kenya[3,5]	1.42	Discolored sediments in association with Oldowan artifacts
Olduvai Gorge, Tanzania[8]	1.2	Thermally altered artifacts (potlids, discoloration)
Wonderwerk Cave, South Africa[12,13]	1.0	Ashed plant remains, burned bones
Gesher Benot Y'akov, Israel[9,10,11]	0.78	Charcoal, thermally altered micro and macro artifacts

[a] 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).

1.1. Background to the study

FxJj20 Site Complex The FxJj20 site complex is located in the Okote Member of the Koobi Fora Formation, which 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 collecting Area 131 in the Karari Ridge region of the Koobi Fora Research area (Fig. 1). Extensive excavations in the FxJj20 site complex recovered tens of thousands of stone artifacts from floodplain silts (Harris, 1978, 1997). 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 m 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 the result of fires. A review of the evidence for the presence of fire at FxJj20 East and FxJj20 Main is found in Table 2.

The locality of FxJj20 AB was 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 (>1 m) found at FxJj20 Main and East were never observed at FxJj20 AB. Prior to the renewed excavations in 2010, there were no large-scale excavations in the FxJj20 site complex since 1979. We implemented a series of excavations at FxJj20 AB designed to increase the recovery of the smallest fraction of the archaeological record. Excavation involved the use of small tools, to recover small materials with minimal modifications to their dip and orientation during recovery. This method allows for the identification of high concentrations of small artifacts without the need to average whole or quarter squares. This enabled us to recover high-densities of small lithic materials. Several high density concentrations were recovered during the renewed excavations. One of these was located directly east of 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, Fig. 2) 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).

FxJj20 Main, Extension 0 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 are curated in the Archaeology division of 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 m 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 equivalent 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 which 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 is possibly an extension of the FxJj20 Main site and, as such, may show the extent of landscapes where it is possible to identify ephemeral, yet detectible, instances where fire and hominin behavior are associated.

Experimental work Much of the archaeological material recovered at the FxJj20 sites is volcanic in origin, either basalt or ignimbrite. It is difficult to visually identify thermal alteration on basalt and ignimbrite as these materials do not display any obvious color change. They do, however, fracture as the result of a rapid rise in temperatures. One such type of fracture is commonly known as a “potlid” (Purdy and Brooks, 1971a, b; Patterson, 1995), and is characterized by an irregular ventral surface with an uneven appearance (Fig. 3). 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 materials are often used to identify the presence of high

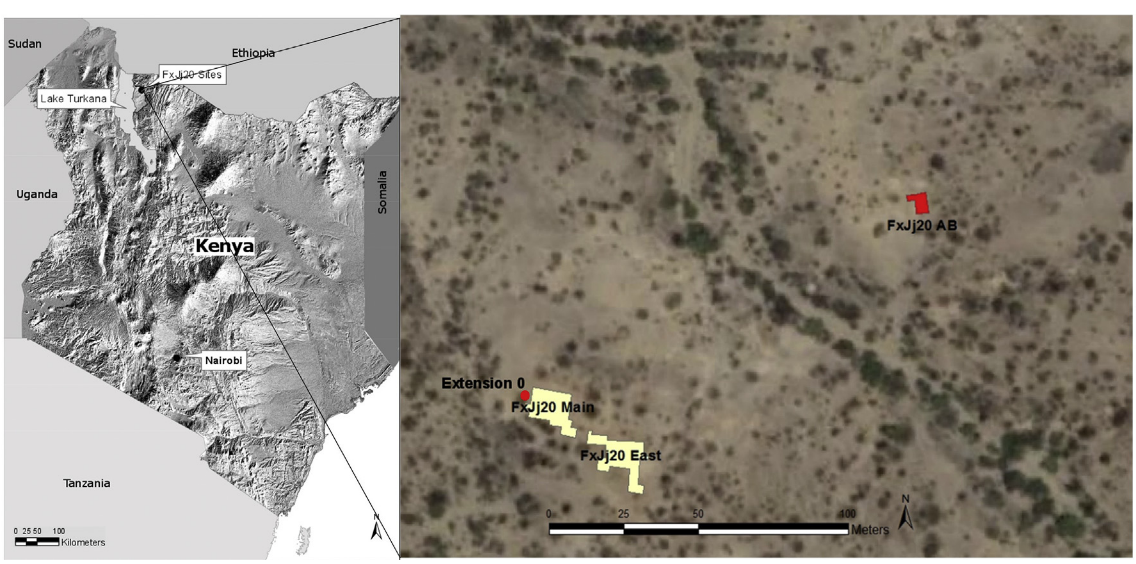

Figure 1. Location of FxJj20 Site complex. FxJj20 East and Main were fully excavated in the 1970s and 1980s; FxJj20 AB was discovered in the 1970s and was reopened for excavation in 2010. Excavation at FxJj20 AB is ongoing. FxJj20 Main – Extension 0 is located outside the northeast corner of FxJj20 Main, was discovered in 2013, and a test excavation was done in 2015.

Table 2
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

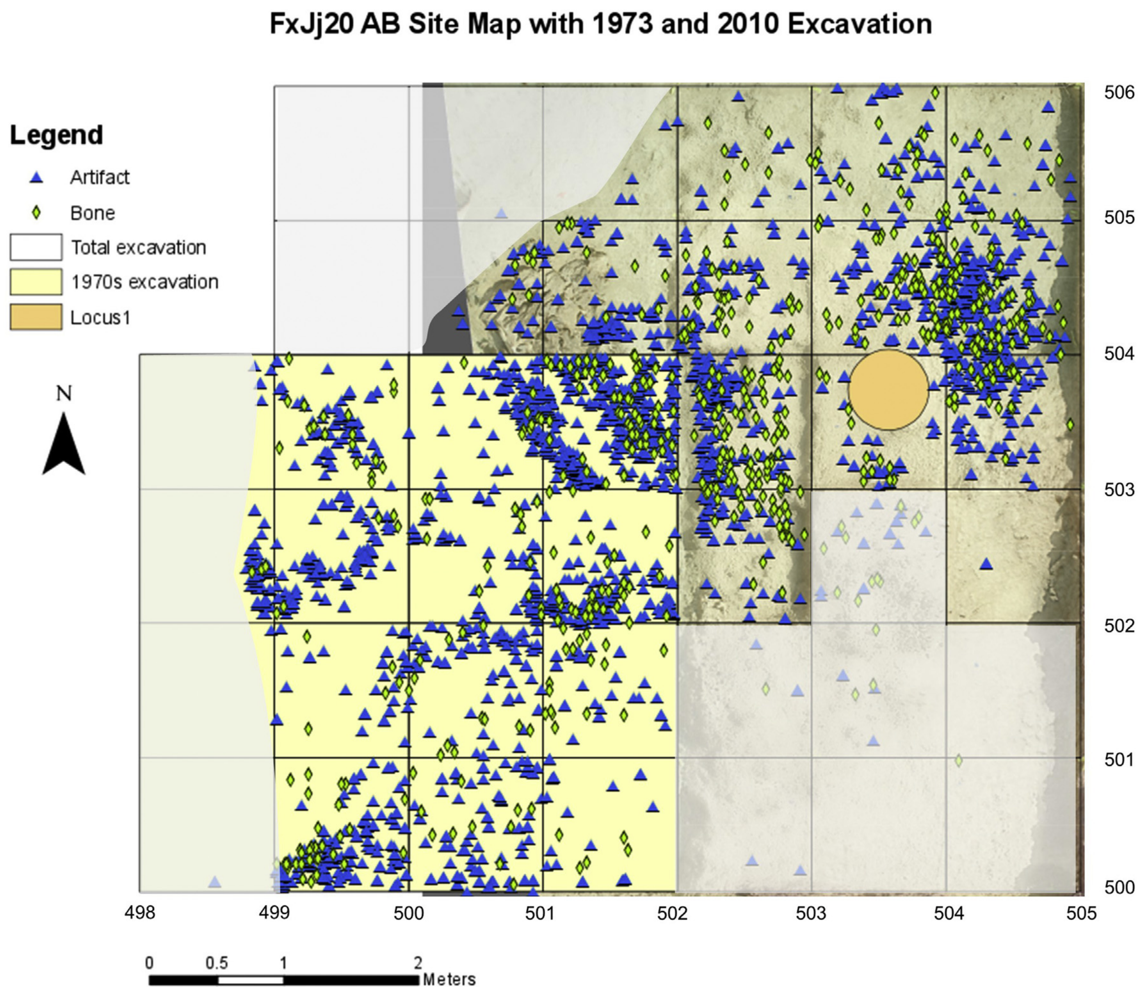

Figure 2. Location of materials after the 2010 excavation season. Locus 1 was identified as an anomalously empty space within a dense cluster of artifacts after the 2010 field season and subsequently partially excavated and sampled. Grey shaded areas represent unexcavated squares and erosional surfaces; materials found within these areas are surface collected. Northing and easting are according to an arbitrary grid, based on the original grid established during the 1970s excavation.

temperature events at an archaeological site (Purdy and Brooks, 1971a, b). However, potlid fractures are not unique to archaeological materials and often natural stones can fracture when exposed to high temperatures (Patterson, 1995). Experimental work associated the FxJj20 sites concentrated on producing heat-fractured materials to study the form of these materials. Our research focused on identifying patterns that might be associated with instances where high temperature, long duration fires occurred in tight spatial association with flintknapping in the past.

Our experimental archaeological work 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.

In this study, we provide a review of the evidence for fire during the Okote Member at Koobi Fora. We attempt to take a multi-facetted approach to identifying features which may be associated with hominin control of fire at the FxJj20 Sites, and provide

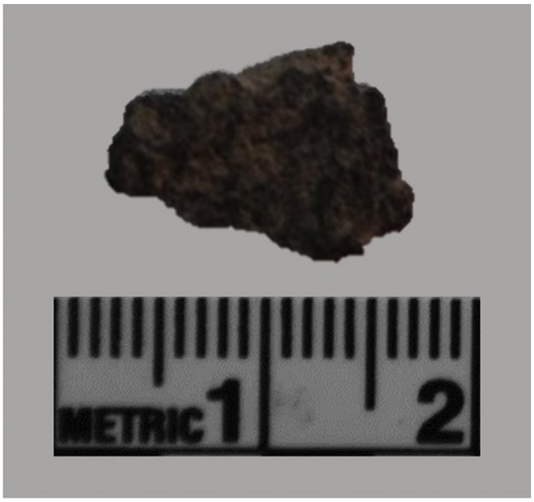

Figure 3. Example of a potlid from experimental field burns. Note the small size, uneven shape, and the irregular surface.

preliminary data on a variety of the methods that may be able to identify combustion features in open-air early Pleistocene contexts. These methods show that it is possible to identify thermally altered materials in the deep past, and it may be possible to associate that fire with hominin behavior. We will then discuss the potential of these proxies for pyrotechnology in antiquity. 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 associating fire and hominin behavior, studied using similar excavation and analysis techniques, would bolster the argument that hominin ancestors in the deep past used fire.

2. Materials and methods

There are two major aspects of this 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. Experimental and actualistic studies make up the second major portion of the study. The experimental work helps to establish a reference collection of burned materials, including stone and sediment.

2.1. 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 records the location to millimeter accuracy (McPherron, 2005). Materials with a discernible long axis were recovered with two sets of coordinates at either end of the long axis to facilitate orientation analysis. The high-fidelity recovery methodology allowed 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 2–4 cm in width and thickness, and 3–7 cm in length. Samples were oriented to magnetic north, cut from the excavation, jacketed in plaster, and then removed.

The area described above as Locus 1 was excavated in cross-section. One-quarter in 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 sedimentary fabric indicated by the micromorphology sample 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 divided into six subsamples. One was left as an unburned sample, and the remaining five were burned in crucibles in a muffle furnace to 300, 400, 500, 700, and 900 °C to create a reference collection specific to the sediment from FxJj20 AB. Muffle furnace burns took place over 6 to 8 h, 1 to 2 h to bring the oven and sample to temperature, 3 h at temperature, and 2 h to cool the furnace. 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 technique, the Optimized Hot Spot Analysis (OHSA), is particularly suited for identifying areas where densities of materials are greater than would be expected by random chance. Optimized Hot Spot Analysis 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. Optimized Hot Spot Analysis uses the Global Moran's I statistic to identify clusters which are significantly different from random. It also prevents false identification of patterns by lowering the threshold for significance in particularly dense concentrations of material (e.g. $p = 0.05$ or 0.001) 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 which 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 explore 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 some sort of behaviorally-based 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, 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.

Comparisons to experimental work conducted by Schick (1986) were performed to determine the likelihood that materials on FxJj20 AB were the result of water related post-depositional processes moving archaeological materials. Schick (1986) carried out a number of site formation experiments, creating sites by knapping materials in different environments and observing the recovery of those materials over time. We compared the numbers of artifacts created and recovered from eight experimental sites affected by low or moderate water disturbance reported in Schick (1986) using a chi-square test with a Bonferroni correction (to correct for multiple comparisons). A comparison of Freeman-Tukey deviates of the materials was done to assess the similarities of the numbers of size classes of the materials in the experimental sites and the archaeological site. We expect that if the materials from FxJj20 AB are similar to the experimental sites after treatment, this would indicate that FxJj20 AB was disturbed by water during the burial process.

An orientation analysis was conducted to look at whether the material on the site is randomly oriented or oriented in a specific direction. If water movement or other geologic processes affected the orientation of archaeological materials, this would result in a preferred direction in artifacts and bone with a discernible long axis (McPherron, 2005). Using NewPlot (McPherron and Dibble, 2010), we calculated the orientations of all materials recovered with a long axis on the site that were mapped in using two points. The angle and direction of these points were plotted on a rose and compass diagram. Eigenvalues were generated for the assemblage, which were plotted in Benn space. The rose and compass diagram can indicate whether there is directionality to the materials recovered, while the Benn space diagram indicates whether the assemblage is planar, isotropic, or linear. An assemblage plotting in the planar corner of the Benn diagram and showing no preferred orientation is likely to be in its original context (McPherron, 2018).

2.2. Experimental work

Actualistic studies are not recreations of past human behavior (Bettinger, 1991), yet it would also be overly conservative to presume that they are not informative of ancient 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) from modern conglomerates in ephemeral rivers in the Turkana Basin in northern Kenya. Both unknapped (i.e. un-worked, unmodified) cobbles/nodules and knapped materials (flakes, core remnants, bifaces) were fired. Knapped and unknapped pieces were 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), between 4 and 8 cm long and less than 4 cm long, including broken flakes and shatter.

Fires were constructed using local wood in a pyramidal manner on sand or silt, swept clean of debris, approximately 1 m 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 [Sper Scientific 800103]) prior to lithics being introduced. Each fire was allowed to cool for at least 24 h 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 which occurred during firing events. The IR temperature thermometer indicated that all fires peaked above 550 °C. Recovered experimental materials were sorted, counted, and described. We recorded details of the specimens (surface textures, cracking) as well as measurements of the specimens (using a digital caliper to the nearest 0.01 cm). Experimentally fired materials are curated in the Archaeology Division of the National Museums of Kenya, Nairobi.

Early firing experiments produced a number of curvilinear angular fragments. We termed such angular fragments “thermal curve fragments” or TCF (Cutts et al., 2015). To determine whether these curved fragments were a result of human behaviors and fire use, we designed a set of experiments to produce TCFs 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, using Euclidean geometry to calculate variables from angle length, angle depth and thickness at midpoint. In ascertaining the symmetry of these TCFs, we measured width and thickness at each end, and at the mid- and quarter-points along the length of each piece to determine the Evenness Quotient (EQ). To determine the EQ of width and thickness across the fragment (Eren and Lycett, 2012; Presnyakova et al., 2015), we calculated the average width and thickness as well as the standard deviation of each measurement, within each experimentally produced piece. We then calculated the average deviation of each individual specimen by averaging the standard deviations of width or thickness to determine evenness of each of these variables. We used this EQ to compare the evenness of these variables in the experimentally produced TCFs to curvilinear debitage produced during knapping exercises. The EQ of all specimens were averaged to get an assemblage-based measure of evenness for the whole sample. A smaller EQ indicates lower variability within individual pieces and the entire sample. The EQ of thickness and width of all TCFs were compared to the evenness of all curvilinear debitage using a two-tailed Student's t-test, performed in Microsoft Excel.

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 (PCA).

3. Results and preliminary discussion

3.1. Archaeology

FxJj20 AB Excavations of FxJj20 AB, between 2010 and 2015, yielded over 3000 artifacts and bone fragments (Fig. 4), 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 3. Bone found on the site is mostly non-identifiable 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).

A breakdown of the stone material included debitage pieces, whole flakes, broken flakes, cores, and potlid flakes (Table 3). 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 (Fig. 5). 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, Fig. 6). Many artifacts on the site (40%) are 20 mm or less in maximum dimension. This high frequency of smaller artifacts

Table 3
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

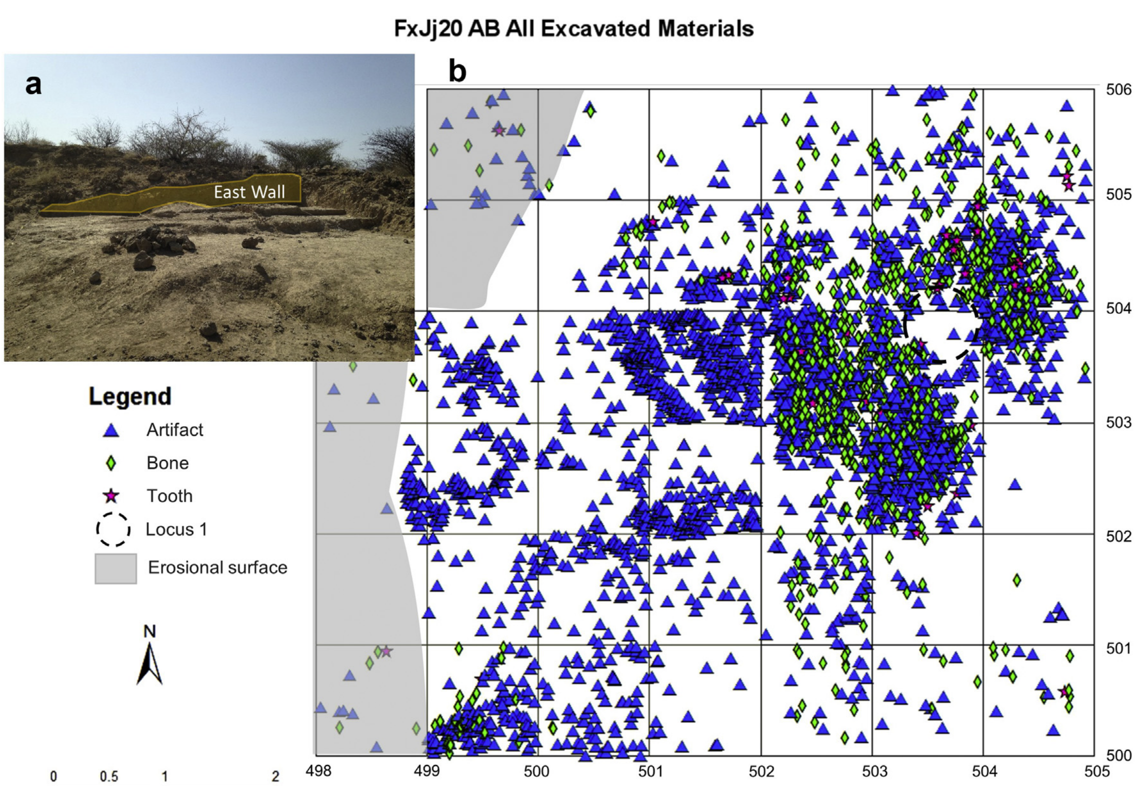

Figure 4. (a) Photograph of site facing southwest across site. (b) Location of all excavated materials at Site FxJj20 AB. Grey shaded areas represent erosional surfaces. Northing and easting of grid based on the original arbitrary grid established in the 1970s.

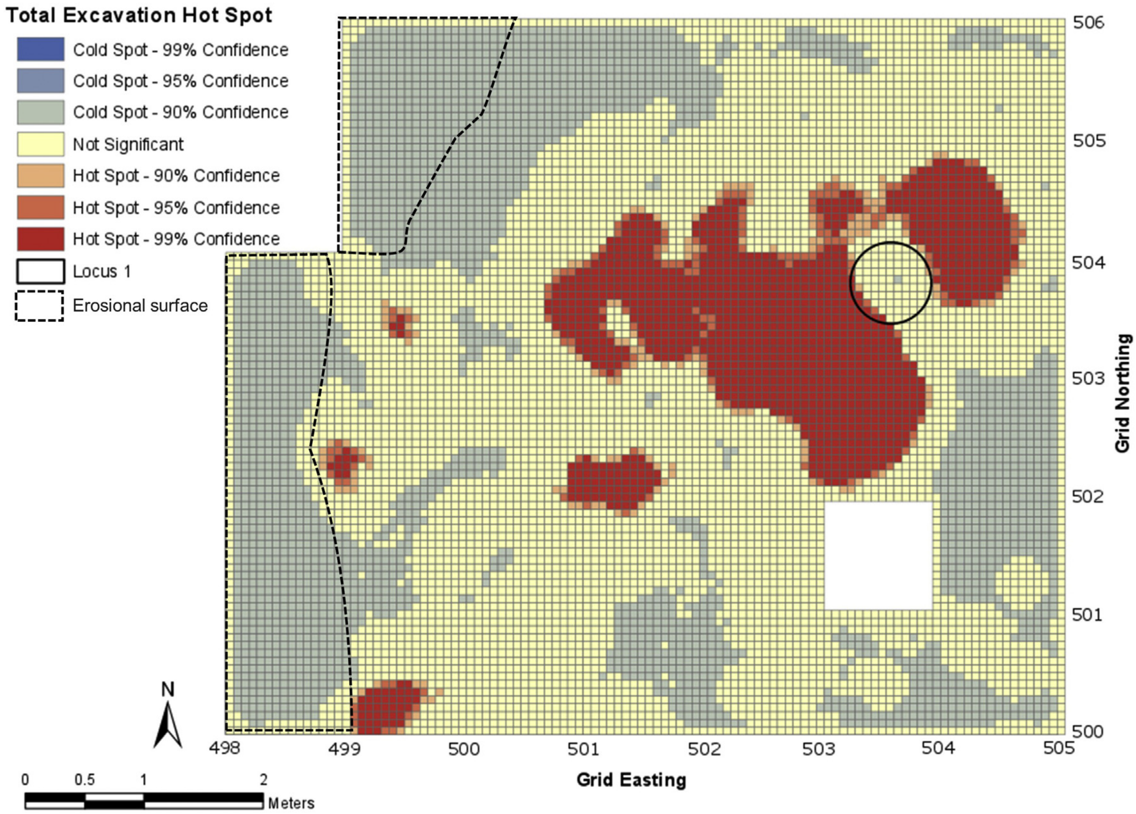

Figure 5. Optimized Hot Spot Analysis (OHSA) of all excavated materials. Most bone and artifacts are concentrated around Locus 1, with some smaller concentrations found further away to the south and west of Locus 1. Areas with no fill are not different from random. Dotted lines represent the erosional surfaces; cold spots located here are the result of data loss as opposed to a lack of material found there (from Hlubik et al., in review). Northing and easting based on the original arbitrary grid established in the 1970s.

suggests that substantial size sorting or winnowing was not part of the post-depositional history of the site (Schick, 1986, 1987). Even mild winnowing of materials from sites will depress the number of small debitage pieces found on a site (Schick, 1986). A Chi-square 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 4). 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 5), 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 experimentally moderately disturbed sites. Additional work investigating the orientation of the artifacts found within the site indicates that there is no preferred orientation of the artifacts, further supporting the undisturbed nature of the site (Hlubik et al., 2017b).

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 also indicates no preferred orientation, 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 7 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.

The vertical dispersion of artifacts on the site (Fig. 8) shows that the frequency of archaeological material has a vertical distribution that parallels that seen in the distribution of burned materials. The mixing of the burned material throughout the archaeological layer indicates that the burning happened before the site was buried and prior to the post-depositional mixing indicated by the micromorphology. The proportion of burned and unburned material in each level is roughly consistent (Fig. 8) and a paired t-test ($t = 0$; $p > 0.05$) shows that these populations are not distinct. We then looked at the vertical dispersion of materials by row, looking at each east to west row of the excavation independently (Fig. 9). This shows that the mixing of the burned materials throughout the excavation is not an artifact of averaging of more complex patterning within the excavation. The pattern exhibited in the

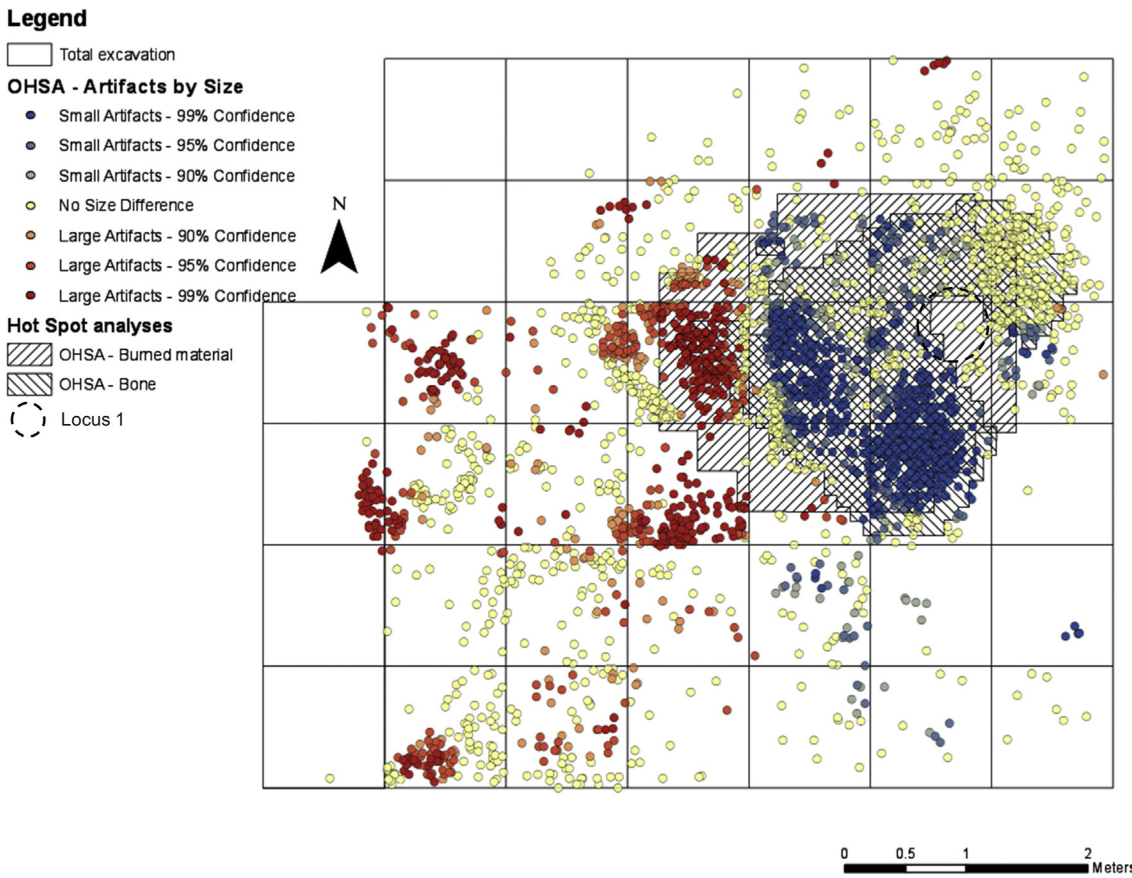

Figure 6. Optimized Hot Spot Analyses (OHSA) of Size-weighted artifacts, burned material, and bone. This shows that burned material, bone, and smaller artifacts (darker colored circles) are clustered together around Locus 1 ($p = 9.77178E\text{-}44$), while larger artifacts (lighter colored circles) 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. Northing and easting based on the original arbitrary grid established in the 1970s.

investigation of the entire excavation is found in each independent east-west transect of the site. This supports the interpretation that burned materials were deposited at the same time as the rest of the archaeological materials and the post-depositional processes affected all materials in a similar manner.

No rubefied patches were found at FxJj20 AB, but rubefied sediment clasts, ranging from 2 mm to 2 cm in size occur throughout the site, intermixed within the archaeological layers, but are concentrated in the densest cluster of artifacts and the south eastern squares of the excavation. Five samples of rubefied sediment, with three dimensional coordinates, and four samples from level bags (where provenience is limited to a 1 m unit that is 5 cm thick), have been tested with FTIR and have been determined to be burned at temperatures over 550 °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 (Fig. 6). Fourier Transform Infrared Spectroscopy 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 (Fig. 6). 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 ($t = -14.096$; $p = <0.001$).

FxJj20 Main, Extension 0 FxJj20Main, Extension 0 was studied as a potential extension of the FxJj20 Main locality. In particular investigations of this locality were focused on the possibility that these sites preserve evidence of possible combustion associated with short-term occupations. Surface collections from this locality included a small number of artifacts (a bifacially worked ignimbrite 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 (Fig. 10). In addition to the FxJj20MExt-0 feature, surface survey located several other similar (rubefied/baked) features in Area 131. Analysis of sediment micromorphology and FTIR samples taken from the feature are ongoing.

3.2. Actualistic studies

Experimental results reveal that thermal alterations to basalts and ignimbrites from the Turkana Basin are in agreement with results from previous studies on fire-cracked rock (Purdy and

Table 4
Chi^2 comparison of a selection of Schick (1986) experimental sites with FxJj20 AB, both before and after experimental treatment.[a]

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*	<0.003	*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

[a] 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. DF = degrees of freedom.

Brooks, 1971a, b; Purdy, 1975). Color, textural and mechanical alterations occur in stone heated in normal campfires. Ignimbrite may explode at medium temperatures (~400°C) while basalt might fracture or spall (only) under higher temperatures (>~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.

Our interpretation of the 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 (Fig. 11). Although similar to the vast majority of angular fragments from archaeological assemblages, closer inspection suggested that 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. Thermal curve fragments appear to be produced in basalt when the materials are exposed to high temperatures for a long duration (>2 h), 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), as opposed to slowly rising temperatures (e.g. in a muffle furnace or slowly heating fire). Thermal curve fractures are regular and scalable; regardless of overall size of TCFs, the EQ of TCFs is more regular than the EQ of unfired knapped debitage. Populations of TCFs are statistically distinguishable from unfired debitage (Table 6). The comparison of evenness between experimentally produced angular fragments ($n = 100$) and experimentally-derived TCFs ($n = 35$) identifies significant differences between these two populations (; $p = 0.007$ [width]; $p = 0.012$ [breadth]). These values indicate that curvilinear angular fragments produced through knapping and thermal curved-fractures (TCFs) are distinct.

A review of 1500 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 (Fig. 11). Our experiments showed that TCFs are not necessarily produced in great numbers, compared to the general high volume of unfired debitage angular fragments found in many sites. Additionally, our experiments indicate that basalt yields TCFs at lower rates compared to more siliceous tool-stone (FxJj20 collections comprise approximately 90% basalt). Generalized knapping debitage—including angular fragments—would be expected to greatly outnumber any collection of heat-altered lithics, including TCFs, in most site collections. Our experiments demonstrate that TCFs form from the application of heat to knapped lithic material; they do not predict how many should be expected from excavations.

4. Discussion

The purpose of the research detailed in this paper by no means confirms the presence of anthropogenic pyrotechnology at FxJj20 AB, although the data presented here does support such a proposition. Instead, this study highlights the potential disjunct between the methods available to investigate the presence of fire at archaeological sites and the context of sites that currently predate the undisputed origin of pyrotechnology.

Table 5
Freeman-Tukey deviates calculated for comparison sites.[a]

	Size class	FxJj20 AB	Site	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site	Freeman-Tukey Deviate	Size class	FxJj20 AB	Site	Freeman-Tukey Deviate
Before	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	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

[a] 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.

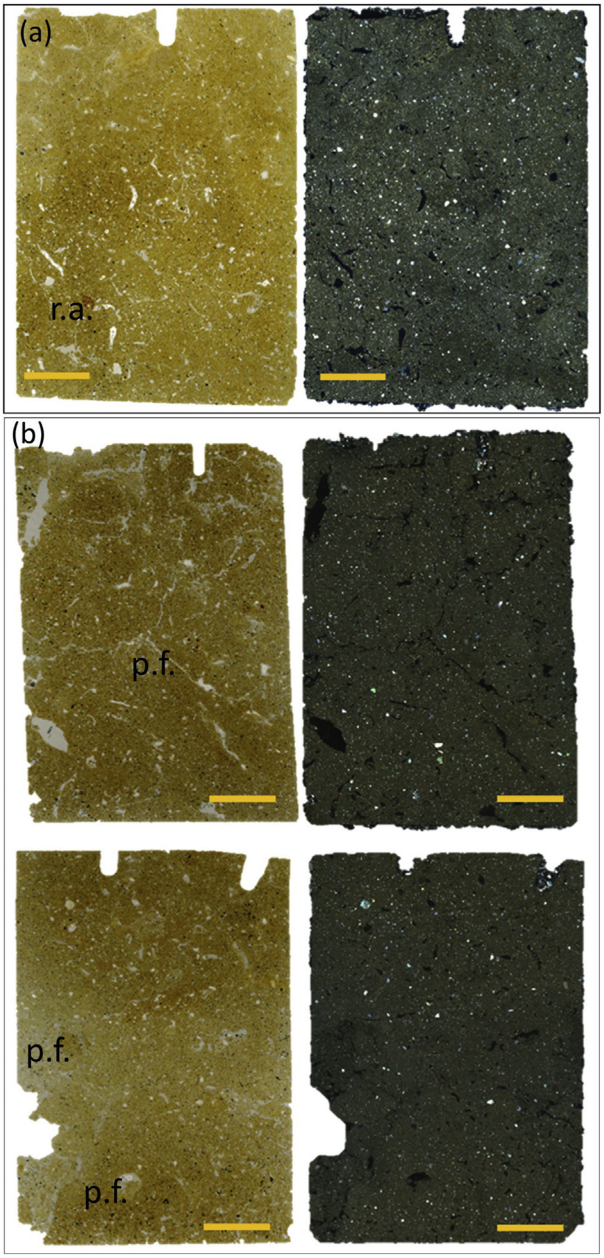

Figure 7. Soil micromorphology at FxJj20 AB. (a) Representative cross polarized light micrograph of the local ground mass (scale bar = 200 μm). Note the micaceous, feldspathic, and quartz composition of the poorly sorted silt and sand and the laminated clay coatings around pores and sand grains. (b) 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 = 1 cm). 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.).

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). Further detailed work is needed to understand the role of fire in human evolution. The work presented here details the evidence of fire at the FxJj20 Site Complex in Koobi Fora, dated to 1.5 Ma. This work demonstrates the presence of fire associated with human behavior. If it is possible to confirm the anthropogenic nature of these materials, this is the earliest documented site in the record to display this association. To understand the impact that pyrotechnology has on the patterns of human evolution we must first document a pattern of fire use throughout the Pleistocene. The work done at the FxJj20 Site Complex demonstrates the applicability of methods and allows us to make suggestions on how to look for fire evidence at open air sites of early Pleistocene age. The work described here is part of a larger project aimed at looking at fire across a landscape. Further inquiries may be able to answer questions surrounding the incidence off fire, both at the level of archaeological sites and a broader landscape scale.

The work at FxJj20 AB provides compelling evidence for the presence of fire that coincides with hominin behavior at this locality. 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.

There is no indication that FxJj20 AB was disturbed to any great extent by post-depositional processes. The micromorphology of the sediments indicates that the site was buried by low-energy water flow, with subsequent soil formation. There are no indicators of large bioturbative agents like roots or trees. Analyses of the artifact size profile is inconsistent with disturbance patterns defined by experimental sites from Schick (1986), while artifact orientations are consistent with a sloped surface where objects have not been moved by flowing water. Analysis of the vertical dispersion of artifacts shows that the distribution of burned materials parallels similar vertical dispersions as seen in unburned materials. This further supports a scenario where the archaeological materials were discarded at a time that was penecontemporaneous with the deposition of the burned materials.

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 additional evidence for fire associated with human activity.

We present 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 coincidence of TCFs and thermal alteration of knapped materials indicates that they may be related. The results of the experimental work suggest that this type of fragment may, in fact, elucidate previously undocumented evidence of burning.

Previous work at the FxJj20 Site Complex as well as other ancient sites, has indicated that phytolith and paleomagnetic studies may also provide evidence on the presence or absence of fire on ancient archaeological sites. Future work will investigate these avenues of investigation.

In the case of FxJj20 AB, burned bone fragments found on the site may be indicative of cooking meat prior to consumption. While this scenario is difficult to prove simply through identifying burned bone, experimental work planned for the future may provide some means to distinguish whether burned bone was fresh or dry at the time it was heated, and this, coupled with spatial analysis, may provide evidence for intentionality of burning.

The prevalence of wildfire on ancient landscapes would have allowed early hominins to experience fire regularly. Future work being planned in the Koobi Fora region will attempt to catalogue the incidence of fire on sites of similar early Pleistocene ages as well as document the incidence of fire available on the landscape.

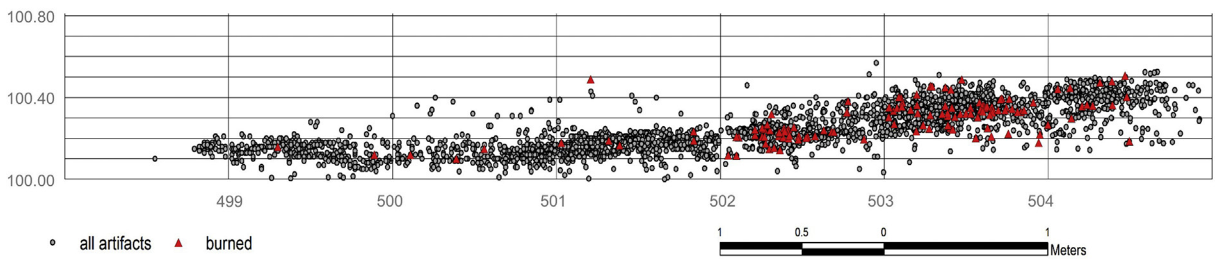

Figure 8. Vertical dispersion of artifacts from west to east. Grey dots represent all materials recovered from the site, while red triangles are burned material. Burned materials appear to be intermixed with the unburned material, suggesting that the materials are contemporaneous. Easting (x-axis) and height (y-axis) based on arbitrary grid system established during the 1970s excavation.

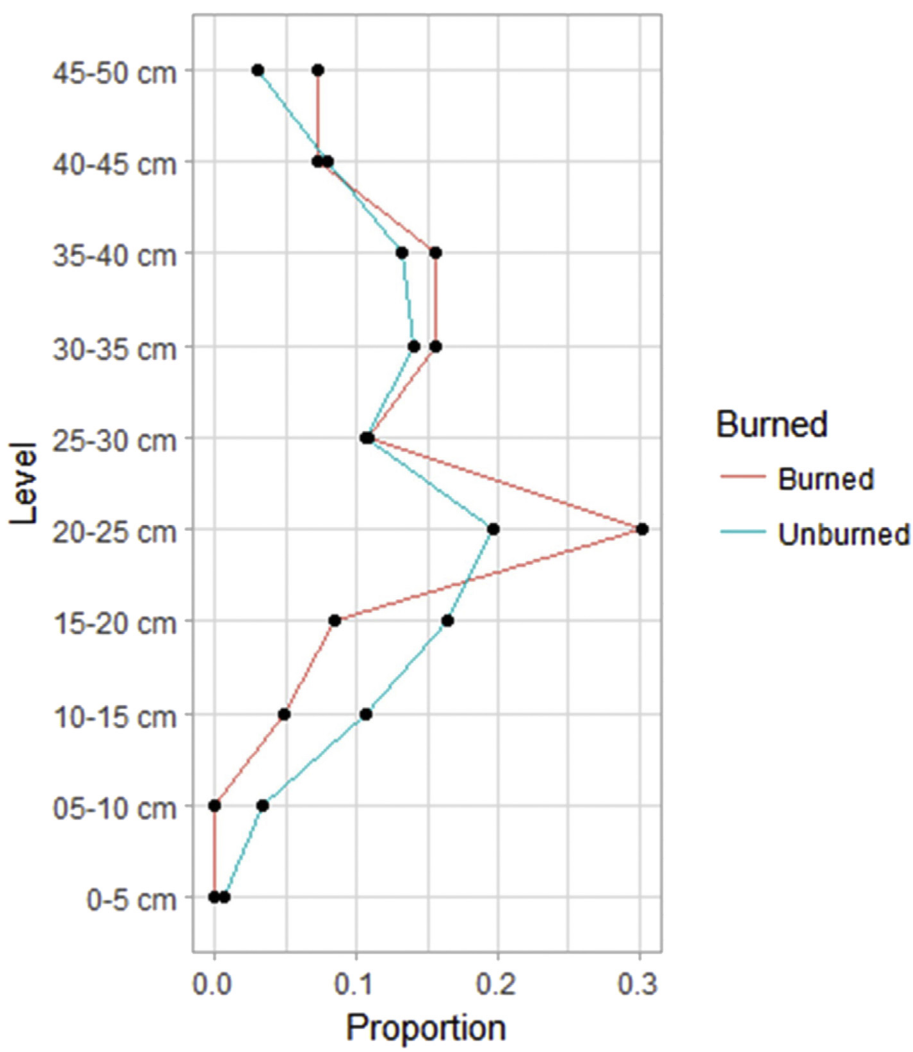

Figure 9. Proportion of materials by level on the site. A paired t-test shows no difference between burned and unburned material ($t = 0$; $p > 0.05$).

Recent studies on long term records from terrestrial cores indicate that proxies of ancient habitats may be able to construct detailed models to look at fire incidence on the landscape (Campisano et al., 2017).

4.1. *Identifying fire in the Early Stone Age: problems and a prescription for future analyses*

The investigation of fire in the early archaeological record requires a number of lines of evidence to determine whether evidence of combustion found at archaeological sites may be the result of hominin behavior. Microscopic approaches to the study of fire have proven successful at identifying fire residues 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

Figure 10. Basalt potlid fracture (on left); shows no bulb of percussion or conchoidal curvature. Recovered from FxJj20 MExt-0. Basalt "potlid" re-fit on battered hammerstone (right). Recovered 20 cm apart within rubefied feature at FxJj20Main-Extension-0. Scale = 1 cm units.

possible to find 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, and it is this line of thought that we believe the future of fire studies must follow.

Reliance on a single proxy is likely to result in a Type II error where the null hypothesis of the absence of fire-use in the Early Stone Age record is supported. However, an investigation that incorporates multiple lines of evidence will provide a more compelling argument that fire is behaviorally associated with hominin activity. 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 of the predominance of open air contexts for these sites. The association of burned materials and hominin activities, as indicated through detailed excavation and fine-grained spatial analysis, may provide insights into combustion events that do not preserve the kinds of proxies typically referred to as diagnostic of pyrotechnology.

Issues with determining the presence of fire in early Pleistocene

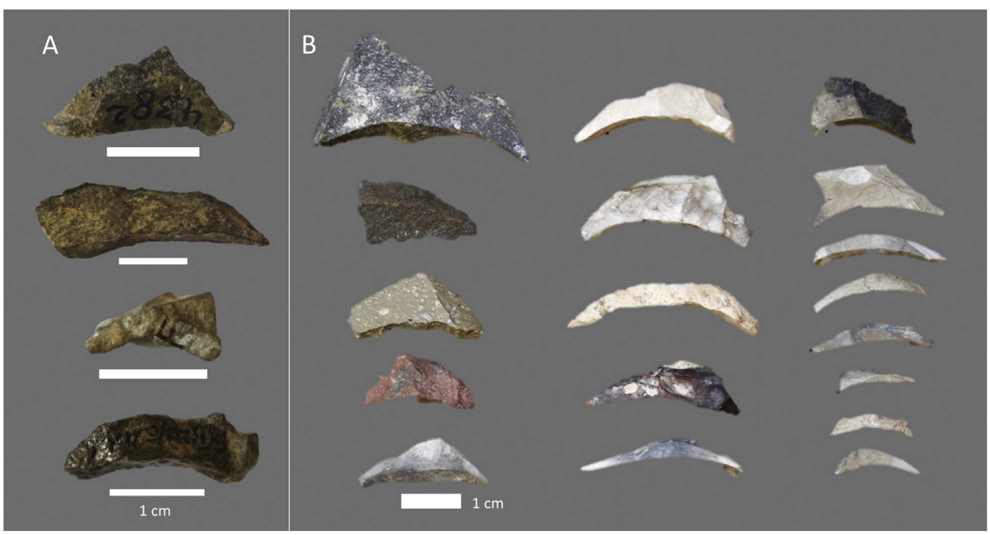

Figure 11. Thermal curved-fractures (TCFs). The potential TCF on top demonstrates statistically similar morphology and was recovered in situ at FxJj20Main during 1970s excavations and labeled "angular fragment" in collections housed at the National Museums of Kenya. On the bottom is an experimentally-derived example from a firing event exceeding 550°C. Scale = 1 cm.

Table 6
Preliminary results comparing curvilinear fractures from knapped and fired debitage.[a]

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

[a] Evenness of width and thickness is calculated by taking measures at defined intervals across a single object. The deviation of each of these measures from the average standard deviation of each measurement across the piece is defined as the Evenness Quotient (EQ). EQ 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 which was subsequently exposed to the fire.

excavated sites from the same time period may be able to identify other instances of fire in the early archaeological record.

It may not be possible to pinpoint the time when our ancestors began to actively produce fire. It is, however, likely 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, and these processes could dramatically affect the manner in which evidence is preserved. Future work in the Turkana Basin will be targeted at not only identifying the incidence of fire on sites of early Pleistocene age, but also on the landscape, both generally and specific to individual environments found throughout the Basin.

5. 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.

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 these data to landscape-scale proxies. To accomplish this, we must begin to identify ephemeral instances of fire that appear 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. The identification of relatively small archaeological occurrences associated with combustion on ancient landscapes may provide the evidence necessary to identify this major transition in human evolution. A number of sites at similar time periods across the landscape with evidence of fire spatially associated with stone artifacts may indicate a consistent use of pyrotechnology and further support fire as a component of hominin behavior during the early Pleistocene.

The question of whether and how human ancestors in the early Pleistocene used pyrotechnology cannot yet be answered. Based on our present knowledge of sites within the Koobi Fora Formation we can document the association of combustion and human behavior on at least one site, FxJj20 AB, dated to 1.5 Ma, with the potential of two or more contemporaneous sites, FxJj20 East, Main, and Ext-0, 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. 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).

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