CAMPFIRE OR WILDFIRE? ADVANCING TECHNIQUES DETERMINING ANTHROPOGENIC FIRE IN THE ARCHAEOLOGICAL RECORD

by

Russell B. Cutts

(Under the Direction of Ervan Garrison)

ABSTRACT

While the use of fire is widely acknowledged as one of humanity's most important discoveries, scientific knowledge of when fire entered our behavioral repertoire is a subject of debate primarily centering on what constitutes clear evidence of human control. Another consideration is preservation bias, in that remains on open-air sites may be disturbed by diagenetic processes. Linked to this second point is the relative lack of clear evidence of anthropogenic fire on many sites dating from 2 million years ago (mya) to 1mya—sites often associated with *Homo erectus*. The derived attributes of *H. erectus* – increased stature combined with larger brain, smaller teeth and shorter gut – appear to indicate an improved diet with enhanced energetic returns, possibly linked to cooking. Alternatively, clear evidence of human associated fire—e.g. hearths in direct association with knapped lithics—has been argued as not significant until much later, ca. 400-300 thousand years ago (kya). Unlike stone, much of the material used in the production of tools is easily biodegradable, therefore very little of the

broader technological culture of early humans is known. This dissertation presents work conducted to utilize a well-preserving and widespread set of artifacts – e.g., stone tools and debitage – to investigate the nature of the human-fire relationship. Experimental, geoarchaeological and excavation data are used to test 1) whether lithics can inform the presence of anthropogenic fire on a site, and 2) whether lithic artifacts associated with *H. erectus* exhibit such heat-altered characteristics. Experimental work investigated whether color and/or fragmentation of stone may indicate the exposure of knapped stone tools to human fire, as suggested by temperature and duration (or "total heat-energy"). Assessment of these experimental lithics using petrographic thin sections further clarified the nature of thermal alteration of tool stone, providing characteristics whose presence suggests the association of knapped stone tools and human-controlled fire. Excavation data is from a new site, FxJj20Main-Extension-0, in Koobi Fora, Kenya, whose Developed Oldowan artifacts are attributed to *H. erectus.* The FxJj20 sites complex, dated to 1.6Mya, have been argued to present potential evidence of hominin control of fire in the Early Pleistocene.

INDEX WORDS: archaeology of fire, anthropogenic fire, thermal curved-fragment, *Homo erectus*, hominin evolution, fire-cracked rock, geoarchaeology, petrography, experimental archaeology

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Fire is widely acknowledged as one of the most important technologies harnessed by humans, and yet the archaeology of fire has not developed as robustly (or quickly) as other avenues of archaeological inquiry, such as dating techniques, the study of ceramics and lithics, even the application of genetic studies to archaeological questions, among many others (Goldberg and Aldeias 2016; Gowlett and Wrangham 2013; Wrangham 2017). The challenges inherent in fire-archaeology are both straightforward and complicated: 1. It is difficult to distinguish between the effects of wild landscape fires and human-controlled fires (in archaeological sites), 2. The debate over "human-control" (of fire) struggles to agree on what constitutes "control", 3. Archaeology cannot perceive the past perfectly, in that the archaeological record is incomplete, 4. Early archaeological sites – e.g., ESA, or Early Stone Age – are often ephemeral, open-air locales that do not readily preserve artifacts and other human-modified materials (with the exception of lithics).

The timing of humanity's initial control of fire is an important but highly debated topic. While some argue that morphological changes exhibited in *Homo erectus* at ca. 1.9Mya infer the control of fire (Aiello and Wheeler, 1995; Wrangham et al., 1999; Aiello and Wells, 2002; Wrangham and Conklin- Brittain, 2003; Carmody and Wrangham, 2009), others counter noting that broadly accepted evidence for human fire is not available prior to 1Mya (James, 1989;

Sandgathe et al., 2011; Roebroeks and Villa, 2011). So, while most archaeologists and paleoanthropologists agree that hominin control of fire was reasonably established by the late Middle Stone Age (ca. 250Kya), the scarcity of sites dated to the ESA in Africa that have claimed to present evidence of hominin fire use, and the equivocal nature of much of that evidence, has resulted in substantial questions with regards to the onset of hominin fire control (Berna et al., 2012; Gowlett et al., 1981; Harris, 1982; Clark and Harris, 1985; Brain and Sillen, 1988; Brain, 1993; Ludwig, 2000; James, 1989; Roebroeks and Villa, 2011; Shimelmitz et al., 2014).

1.1 Background to the Dissertation

1.1.1 Challenges in the archaeology of fire

The remains of fire – char, ash, smoke – are ephemeral and do not readily preserve in the archaeological record, neither do they indicate *how* the fire was created (natural or anthropogenic). Clear evidence of human-controlled fire—e.g., stone-lined hearths with multiple layers of ash and charcoal in direct association with lithic artifacts, tool-marked bone, etc.—may be unequivocal when found as such (Aldeias et al., 2012; Alperson-Afil, 2007; Bentsen, 2014; Berna et al., 2012; Berna and Goldberg, 2007; Courty et al., 2012; Goldberg et al., 2012; James, 1989; Karkanas et al., 2007; Roebroeks and Villa, 2011; Shahack-Gross et al., 2014; Shimmelmitz et al., 2014). This type of clear evidence of human controlled fire is not always present, even in modern foraging societies (Brooks and Yellen, 1987; Mallol et al., 2007; Parker et al., 2016). Further, fire evidence in open-air sites, especially ESA sites, can be challenging to

determine in that natural wildfires can affect remains, and taphonomic processes may degrade, remove or relocate materials.

Identifying human-controlled fire in the archaeological record typically relies on a few common artifacts, features and material remains. These may include burned wood, shell, or bone associated with other archaeological features. Many also have clear indication of human interaction (e.g., tool or butchery marks, midden-context or activity areas)(Berna et al. 2012; Berna and Goldberg 2007; Karkanas et al. 2007; Shahack-Gross et al. 2014). Hearth features, too, are regularly documented in the archaeological record; these are more common from the late Middle Stone Age (MSA) through the Holocene and are typically interpreted to have been produced by *Homo neanderthalensis* (Neanderthals) or *H. sapiens* (AMH or modern humans) (Aldeias et al. 2012; Bentsen 2014; Courty et al., 2012; Goldberg et al. 2012; James 1989; Roebroeks and Villa 2011). Hearths increase in frequency and complexity in later sites, and may be defined by stones, berms, or through re-use, sweeping/cleaning and concentrations of burned remains; often these are used to infer regular use of fire (or, "fire at will") (Karkanas et al. 2007; Mallol et.al 2013; Shahack-Gross et al. 2014; Shimelmitz et al. 2014). It has been noted, however, that hearths—especially stone-lined fireplaces—may not be common behavior in ephemeral campsites of foraging bands of hunter-gatherers, even into modern times (Binford 1980, 1983; Brooks and Yellen 1987; Mallol et al. 2007; Parker et al. 2016). Alternatively, hearths may feature in 'home-base' or camps (*sensu* Binford), whether they are open-air sites with structures, or cave-sites showing long-term occupation (Alperson-Afil 2008; 2012; Berna and Goldberg 2007; Karkanas et al. 2007; Roebroeks and Villa 2011; Shahack-Gross et al. 2014; Shimelmitz et al. 2014).

Other methods for inferring anthropogenic fire include pyroliths (stony material with indications of fire exposure), pyrolized phytoliths (siliceous "stones" from plant structures exposed to fire), rubified (reddened, oxidized) sediments as well as discrete concentrations of charcoal and ash that suggest a hearth or campfire (Albert et al. 2012; Aldeias et al. 2016; Bellomo 1993; Berna et al. 2012; Courty et al. 2012; Cutts et al. 2015, 2016; Goldberg et al. 2012; Ludwig 2000). Remains of ceramics (pottery) also clearly indicate human control of fire; these can include both ceramics manufactured as containers as well as figurines (the earliest of which are found in Eurasian sites dated to the early Upper Paleolithic, ca. 20-30Kya; (Vandiver et al. 1989).

Even with these lines of evidence for human-controlled fire, equifinalities often undermine clear determination that any given evidence of combustion is, actually, produced or maintained by people. Wildfires may sweep across archaeological sites leaving misleading evidence in the form of char, ash, burned wood or modified stone. As a result, recent archaeological reviews have pushed for clarity in arguing evidence for human control of fire (Sandgathe and Berna 2017, and others in that volume). For example, a campfire will demonstrate discrete, extremely localized changes due to exposure to high heat (e.g., rubified sediment, consolidated/hardened, and distinct from surrounding, unfired sediments)(Aldeias et al. 2016). These discrete features will also clearly be in association with other evidence of anthropogenic activities, such as middens, lithic flaking debitage, stone tools, butchered faunal remains and the like (Alperson-Afil 2007; Shipman and Rose 1983). It is this *clear association* of discrete, high-energy, localized (and perhaps long-duration or re-used) fire events with anthropogenic behavior that strengthens the argument(s) for anthropogenic fire. Any interpretation of a hearth lacking conventional features—stone-lined, charcoal, ash-lenses in

association with clear human activities—will likely be scrutinized…"[H]uman fire breaking free will resemble a wildfire, but a wildfire 'burning small' will not exactly mimic hearths" (Gowlett and Wrangham 2013:9).

Another challenge to anthropogenic fire evidence (especially from early sites) is the reality of taphonomic impacts. It is uncommon for charcoal, ash, burned bone, shell and the like to persist in sites older than ~700 Ka without particular conditions that promote preservation (e.g. water-logged/anaerobic or cave deposits). In particular, open-air exposure (wind, rain, erosion, diagenesis) tends to erase fire evidence (ash, charcoal) commonly found in protected (e.g. cave, rockshelter) or younger sites (<700 Ka).

1.1.2 Who first used fire? Evolutionary and archaeological perspectives

Carnivory has long been attributed to the morphological changes in the hominin lineage beginning with *Homo erectus*, ca. 1.9Mya. Meat, being a higher-quality diet with greater energy returns, is touted as a more easily chewed food whose acquisition could account for the reduction in masticatory apparatus and digestive system while increasing brain-size (Aiello & Wheeler 1995; Aiello & Wells 2002; Blumenschine & Pobiner 2007; Milton 1999; Organ et al. 2011; Speth 1989). Evidence for carnivory in the genus *Homo* begins potentially as early as 3.4Mya (McPherron et al. 2010), becomes more widespread by about 2.5-2.0Mya (Ferraro et al. 2013; Semaw et al. 2003). While meat-eating increases the amount of fat, protein and essential amino acids in the diet, it also incurs greater water needs and increases the basal metabolic rate and doesn't account for a non-carnivory digestive system's inefficient processing of meat (Aiello and Wells 2002; Milton 1999). There are also inherent dangers in over-reliance on lean meat for

energy needs as well as risks associated with bacteria and parasites (Cordain et al. 2000; Ragir et al. 2000; Smil 2002; Smith et al. 2015; Speth 1987). *Cooking* meats – scavenged or hunted – would both reduce the pathogenic concerns and increase efficiency of digestion, making nutrients more readily bioavailable (Boback et al. 2007; Smith et al. 2015).

In 1999 Wrangham and colleagues introduced what has now been termed *The Cooking Hypothesis* which attempted to explain how the morphological changes in *Homo erectus* could be linked to the use of fire (Wrangham et al. 1999). These changes – overall increase in body size, relative and overall increase in brain size, reduction in tooth size and jaw size, shorter digestive system and the loss of adaptations for an arboreal lifestyle – could potentially be explained by the acquisition of fire into hominin behavior repertoire. Cooking is a very efficient, effective, manner of preparing food, be it plant, mushroom or meat, and studies support the notion that cooking increases the caloric returns of all these foods (Boback et al. 2007; Carmody, Weintraub, & Wrangham 2011; Carmody, Weintraub, & Wrangham 2010; Carmody, Weintraub, & Wrangham 2012; Carmody & Wrangham 2009). Further, cooking denatures toxins and would increase the number of available foods, as well as reduce pathogens (bacteria and parasites) in scavenged meat sources, potentially allowing meat to form a more substantial aspect of hominin diets (Leopold and Ardey 1972; Smith et al. 2015; Stahl et al. 1984).

The acquisition of fire into the behavioral repertoire of hominins is probably a three-stage process: 1. Access to opportunistic use of wildfire (often by lightning ignition), 2. Development of management techniques that enable humans to keep fire alive and relocate it (smouldering techniques, torches, ember-carrying), utilizing the same fire time-and-again, and 3. Ability to create fire “at-will” (hand-drill, strike-a-light, fireplow, etc.). Opportunistic use of fire may well

have begun early in the Pleistocene, but, as mentioned above, clear evidence of controlled fire in ESA sites is neither widespread nor widely accepted (James 1989; Sandgathe et al. 2011; Sorensen, Roebroeks and van Gijn 2014; Roebroeks and Villa 2011).

Although some of these lines of evidence for human-controlled fire may be quite common (and unquestioned) in later sites (late MSA/Upper Paleolithic and Holocene periods), establishing the clear association of humans and their control of fire back into much earlier times (early MSA and Pleistocene ESA hominin sites) remains significantly challenged. Some early sites with reported fire evidence, while ambiguous and not widely accepted, include Gadeb and the Middle Awash (ca. 1.4-0.7Mya) in Ethiopia (Clark and Harris 1985; Clark and Kurashina 1979), Swartkrans (ca. 1.2Mya) in South Africa (Brain and Sillen 1988; Brain 1993), Chesowanja (ca. 1.4Mya) in the Baringo Basin, Kenya (Clark and Harris 1985; Gowlett et al. 1981) and Olduvai Gorge (ca. 1.5Mya) in Tanzania (Ludwig 2000). Much of the evidence from these equivocal sites includes discolored stone artifacts (argued to be heat-induced, e.g., reddening, blackening) and baked clay clasts, burnt bones (later counter-argued to be manganese staining) and associations with stone artifacts and fossils.

A few of the earlier, yet more widely accepted, sites with evidence of human-controlled fire are Beeches Pit (England, ca. 400Kya), Gesher Benot Ya-Aqov (Israel, 790Kya) and Wonderwerk Cave (South Africa, ca. 1Mya) (Alperson-Afil and Goren-Inbar 2010; Berna et al. 2012; Gowlett et al. 2005). The evidence at Gesher Benot Ya-Aqov includes burned wood, seeds and lithics whose spatial considerations infer an interpretation of human fire and “phantom hearths” (Alperson-Afil and Goren-Inbar 2010). At Beeches Pit, England, a 400Kya site, a knapper purportedly sat before a fire and flaked stone tools. Three of these flakes made their way

into the fire, which subsequently burned them red (Gowlett et al. 2005; Preece et al. 2006). Studies at Wonderwerk Cave utilized micromorphological analysis of sediments to infer the presence of discrete and localized campfire activities as indicated by ashed plant remains (Berna et al. 2012).

The identification of clearly anthropogenic fire on all of these sites remains somewhat equivocal. While these sites present evidence suggesting hominins controlled fire in the Early Pleistocene, none demonstrate a suite of these characteristics (outlined previously) as unequivocal evidence typical of human-controlled fire (James, 1989; Sangathe and Berna 2017). It becomes important, then, to continue to develop new techniques that help clarify whether evidence of fire is, in fact, due to hominin activity as opposed to the effects of natural wildfires (Aldeias et al. 2016; Binford 1981; Cutts et al. 2015, 2016; Goldberg and Aldeias 2016; Hlubik et al. 2017, 2019; Oestmo 2013). Sandgathe and Berna (2017:169) agree, stating "…our understanding of the relationship between prehistoric fire and the resulting archaeological residues depends heavily on an understanding of the interaction between fire and its immediate environment and the residues and alterations that result from this interaction. This understanding relies very heavily on experimental work."

Regardless of the difficulty in determining clear evidence of anthropogenic fire on these ancient sites, some researchers have suggested that the inherent advantages of the control of fire – cooking, protection, warmth, purification of water, etc. – are so significant that, once hominins began experimenting with fire, the selective pressure(s) for this behavioral trait would be strong (Wrangham et al. 1999; Wrangham and Conklin-Britton 2003; Gowlett and Wrangham 2013).

1.1.3 The FxJj20 Sites Complex in brief

Another location reported to have evidence of potential controlled-fire by hominins is the FxJj 20 site complex on the Karari Ridge, Koobi Fora, Kenya (Barbetti 1986; Bellomo 1994; Bellomo and Kean 1997; Harris 1978). Excavations in the 1970s revealed peculiar, discrete, rubified "patches." These were interpreted as possible hearths, are circular and approximately 1 meter in diameter (Harris 1978, 1997). With recent excavations (since 2013) that include FxJj20Main-Extension-0, there are now ten (10) reddened patches at this complex. Bellomo (1993, 1994, 1994b) conducted further studies at FxJj20 and, although not entirely conclusive, thermoremanent signatures suggested that the patches were heated, and distinct from the surrounding tuffaceous silts. Other studies at the FxJj20 sites have indicated that some lithic material and phytoliths show evidence of being heated (Ludwig 2000). Recent excavations at FxJj20AB and FxJj20Main-Extension-0 are yielding evidence that corroborates the interpretation that fire was controlled by hominins at these localities (Cutts et al. 2016; Hlubik et al. 2017, 2019).

1.1.4 Why study fire-cracked rock?

Pyroliths are commonly referred to as fire-cracked (or possibly fire-modified) rock. Fire-cracked rock (FCR) is often referenced when associating human activity and fire. A literature review provides no real consensus or standardized description of FCR, but includes traits like "color change [red, white and/or black], surface cracks, and irregularly fractured sections" (Nakazawa et al. 2009:687). FCR may manifest as angular shapes described as jagged, curvilinear, contorted, irregular, spall, pot-lid, crenulated, etc. (Jackson 1998; Latas 1992; McParland 1997; Taggart 1981; Thoms 1986, 2008, 2009; Oestmo 2013). Thus, FCR usually

indicates materials that are discolored (reddened, blackened, whitened) and broken (often characterized as “shatter”, “pot-lid” or thoroughly cracked) (McDowell-Loudan 1983; Patterson 1995). Shatter may encompass debris that is large or small, but typically shows morphology that is distinct from unfired knapping debitage (Mercieca 2000). For example, shatter is often described as slivers or fragments that may not clearly show platform, bulb of percussion, ripple marks or other signs of conchoidal fracture (Purdy 1975; Purdy and Brooks 1971). When cobbles are used as fire-furniture (border, props, boiling rocks, etc.) they will often suffer catastrophic fracture, with cracking throughout that results in crumbling (Nakazawa et al. 2009). They will commonly display discoloration (blackening, reddening) and cracking, as well as becoming considerably more friable (Jackson 1998; McParland 1977; Rennie 2001). Roasting stones show evidence of repeated heating. This may be deep, fatal cracking, or even loss of cohesion (House and Smith 1975; Jackson 1998; Nakazawa et al. 2009). Used roasting stones may end as a pile of “burned rocks” (Taggart 1981; Thoms 1986, 2008, 2009).

The effects of wildfire could confound clear anthropogenic associations in FCR, however, as all the above characteristics can be produced absent human control of fire. Furthermore, these characteristics have not generally been clearly defined or quantified through rigorous and repeated experimental and statistical analysis (but see Oestmo 2013). The problem in part may be how FCR characteristics are often identified: field settings, where an experienced archaeologist mentors apprentices regarding perceptions of FCR. Fire-cracked rock may, in fact, be so prevalent from later sites that the analysis of it is comprised simply of gross weight and then tossed or shelved (Jackson 1998; Nakazawa et al. 2009). As Jackson (1998:2) states, "This thesis reports the results of research on a subject many consider not worth studying: fire-cracked rock (FCR) and FCR features...We excavated numerous FCR features and recovered many

artifacts...while FCR was discarded in backdirt piles." Nakazawa et al. (2009:692) clarifies with "FCR have not often been seriously treated as study subjects in the research tradition of the European Paleolithic..."

A more recent term, fire-modified rock (FMR), somewhat broadens the classification of lithic material changed by exposure to heat. Whereas FCR infers shatter and cracking, FMR may reference textural, luster, color and mechanical modifications more associated with "engineering" raw materials towards a more useful, flakeable product (Brown et. al 2009; Flenniken and Garrison 1975; Jackson 1998). For example, heat-treatment may improve control of poor-quality silcretes, and even good quality material can be enhanced (Brown et al. 2009; Domanski and Webb 1992; Schmidt et.al 2013). Visual cues that heat-engineering has occurred include color changes (moving towards oranges, reds, browns, purples) and luster modification (Olausson and Larsson 1982; Rowney and White 1997). Siliceous rock is often glassy and reflective. Heat-treated material will appear more waxy and "slick," compared to untreated materials. This indirect-heating process may have arisen in human industry around 100Kya and is distinct from the destructive nature of direct high-heat resulting in FCR (Brown et al. 2009; Wadley and Prinsloo 2014).

In all of the above-mentioned interactions between fire and stone, the effects of fire on rock have not been studied comprehensively. While some types of stone may change color when heated (e.g., chert, chalcedony), others cannot be effectively classified as raw or burnt with visual inspection (e.g., basalt, andesite). Natural agents may also affect stone in ways similar to fire (e.g., manganese staining, oxidation, chemical weathering, freezing, etc.; Blackwelder 1927; Shahack-Gross et al. 1997), and landscape fires (i.e. "wildfires") may mislead interpretations by modifying surface rock not otherwise derived by human activity, or sweep across archaeological

sites and affect anthropogenic lithic scatters. The same is true of wildfire's effects on other artifacts (e.g., wood, bone, seeds, shell, etc.). Although careful, experienced, study can differentiate natural weathered exfoliation from a heat-induced pot-lid fracture, the nuanced characteristics are not necessarily widely acknowledged within archaeology.

Whereas lithics preserve well and may survive the millions of years, taphonomic processes make ephemeral many of the features used to identify fire: ash, char(coal), burnt bone, pyrolized phytoliths, etc. may be readily lost, or potentially (re-)deposited out of context. Second, natural agents may also affect stone in ways similar to fire (Blackwelder 1927). It is often noted that 'absence of evidence is not evidence of absence,' yet there persists in archaeology a tendency to apply a false dichotomy in archaeological fire research. Evidence of fire in the archaeological record is usually relegated to a presence versus absence of ancient combustion (Gowlett and Wrangham 2013). These and other problems plague the understanding of using stone artifacts to understand the human influence on fire in the past.

It is clear that "the archaeology of fire is not a mature science" (Gowlett and Wrangham 2013:6); this is due in part to the inherent challenges in clearly establishing the anthropogenic origin/association of these lines of evidence for human control of fire. Recent decades have seen the development of critical approaches and new quantitative methods to address this gap (see Sandgathe and Berna 2017, and other articles in that volume). These include thermoremanent magnetism, thermoluminescence, micromorphology of sediments and soils, electronic spin resonance, Fourier-Transform Infrared Spectroscopy (FTIR), residue analysis as well as more comprehensive excavation procedures that emphasize the recovery of even the smallest artifacts to clarify spatial arrangements of activity areas such as hearths (sometimes termed "phantom hearths") (Alperson-Afil et al. 2007, 2008; Bellomo 1993, 1994; Berna et al. 2007; Berna and

Goldberg 2007; Courty et al. 2012; Garrison 2003; Goldberg et al. 2001; Hlubik et al. 2019; Mallol et.al 2013).

Micromorphology, in particular, has demonstrated significant potential in inferring or clarifying the presence of fire, and its likely (anthropogenic) origin. In addition to identifying microcharcoal and ash lenses otherwise not apparent to the naked eye, this technique incorporates the analysis of many other materials (e.g., phytoliths, starch grains, fragments of bone, wood and shell, etc.) that may provide information on the nature of a suspected burnt feature. For example, identifying pyrolized phytoliths to genus or possibly species level may allow inference or determination of the type of fuel(s) used in the combustion event (Albert et al. 2012; Rowlett 2000). Indeed, micromorphological study has the ability to clarify that suspected evidence of human-controlled fire was, in actuality, *natural* in origin, such as Goldberg and colleagues (2001) re-examination of sediments from the famous site of Zhoukoudien (China). The reported ash lenses at Zhoukoudien previously interpreted as hearths were determined to be more likely in-wash or perhaps sediments spontaneously combusted from bat guano.

The identification of clearly anthropogenic fire on early Pleistocene sites is equivocal. While these sites present evidence suggesting hominins controlled fire in the ESA, none demonstrate a suite of the characteristics (outlined above) as unequivocal evidence typical of human-controlled fire (James, 1989; Sangathe and Berna 2017). It becomes important, then, to continue to develop new techniques that help clarify whether evidence of fire is, in fact, due to hominin activity as opposed to the effects of natural wildfires (Aldeias et al. 2016; Binford 1981; Cutts et al. 2015, 2016; Goldberg and Aldeias 2016; Hlubik et al. 2017, 2019; Oestmo 2013). Sandgathe and Berna (2017:169) agree, stating "…our understanding of the relationship between prehistoric fire and the resulting archaeological residues depends heavily on an

understanding of the interaction between fire and its immediate environment and the residues and alterations that result from this interaction. This understanding relies very heavily on experimental work."

The research presented in this volume works to develop complementary techniques to these (above detailed) methods of distinguishing the effects of wildfire versus anthropogenic fire on artifacts in archaeological sites. While the novel methods presented below can be applied to most any archaeological site from any time period, they may be particularly valuable when applied to the important question of when human ancestors first began to acquisition fire into their behavioral repertoire. More specifically, these methods utilize one of the most common and long-lasting types of artifact – lithics – by investigating a subset (FCR/FMR) that is regularly recovered yet has been chronically understudied. This dissertation is comprised of three papers, one published, another submitted for publication and a third readied for submission, presenting results of research that 1. Quantify a peculiar and consistent form of FCR, which we term "Thermal-Curved Fragment" (TCF) that indicates an interaction of knapped stone with temperatures and durations associated with campfires, 2. Investigate heat-induced macroscropic and microscopic changes in common tool-stone evaluated using optical petrography and scanning electron microscopy (SEM), and 3. The excavations during field seasons 2013-2016 of the 1.6Mya FxJj20Main-Extension-0 archaeological site in Koobi Fora, Kenya, with the goal of applying these novel methods to archaeological materials representing potential evidence of the hominin control of fire.

The first paper (published), "Thermal-Curved Fragments: A method for identifying anthropogenic fire in the archaeological record," reports the identification of a specific type of FCR – thermal-curved fragments – that quantifiably infer the interaction of knapped (hominin

derived) tool-stone with temperatures and durations commensurate with campfires (vs. wildfires).

The second paper (submitted, under review), "Mineralogical and Textural Alteration of Heated Tool-Stones: advances in understanding fire-cracked rock," investigates macroscopic and microscopic modifications in commonly used tool-stone – e.g., chalcedony, ignimbrite, basalt, andesite – under varying heat and duration exposure. Heated lithic material was subsequently thin-sectioned and examined using an optical petrographic microscope and scanning electron microscopy in effort to determine structural and mineralogical changes in the fabric of these materials that could be linked to temperatures and durations associated with campfires.

The third paper (readied for submission), "Evidence for *Homo erectus* fire use: excavations at the new site FxJj20Main-Extension-0, Okote Member, Koobi Fora, Kenya," reports on archaeological survey and excavation of a newly discovered rubified feature associated with the FxJj20Main site, ca. 1.67Mya. Associated artifacts and features are interpreted as providing corroborating evidence that *Homo erectus*, at 1.6Mya, may have been using fire.

CHAPTER 2

THERMAL CURVED-FRAGMENTS: A METHOD FOR IDENTIFYING ANTHROPOGENIC FIRE IN THE ARCHAEOLOGICAL RECORD[1]

[1] Cutts, R.B., S. Hlubik, R. Campbell, J. Muschinski, P. Akuku, D.R. Braun, D.B. Patterson, J.J. O'Brien, E. Garrison and J.W.K. Harris. 2019. *Journal of Archaeological Science*. 106:10-22.

Abstract

The archaeology of fire is a developing field. One challenge centers on equifinality: distinguishing the affects of wildfire versus anthropogenic fire. Especially where evidence for control of fire by humans in the early Pleistocene remains debated, there is little consensus regarding what constitutes clear evidence of *human-control*. Another concern is preservation bias, which reduces clearly identifiable archaeological signatures of fire. In this paper we argue that a peculiar lithic angular fragment—termed *thermal curved-fragment* (TCF)—exhibits statistically distinct, quantitative evidence of the confluence of human-knapped stone tools and exposure to a high-energy, long-duration, ground-level fire (i.e., campfires). Experimental TCFs are described and compared to unfired knapping debitage, natural exfoliations and suspected archaeological TCFs. The provenance of these archaeological specimens has previously been argued to infer hominin-controlled fire at 1.5-1.6Ma at the Koobi Fora Formation. We also present data from experiments exposing stone flakes (arranged as "scatters") of similar raw materials to those found in the Koobi Fora Formation to USDA prescribed burns in a variety of conditions approximating landscape fires. Results indicate that TCFs are formed specifically where (previously) knapped stone is exposed to high-energy ground level fires, similar to those seen in ethnographic campfires. Our analysis indicates that TCFs can be used in conjunction with other lines of evidence indicating the presence of anthropogenic fire in the archaeological record.

2.1 Introduction

2.1.1 What comprises evidence of human-controlled fire, and how do we know that rock is fire-cracked (FCR)?

Clear evidence of human-controlled fire—e.g., stone-lined hearths with multiple layers of ash and charcoal in direct association with lithic artifacts, tool-marked bone, etc.—may be unequivocal when found as such (Aldeias et al. 2012; Alperson-Afil 2007; Bentsen 2014; Berna

et al. 2012; Berna and Goldberg 2007; Courty et al., 2012; Goldberg et al. 2012; James 1989; Karkanas et al. 2007; Roebroeks and Villa 2011; Shahack-Gross et al. 2014; Shimelmitz et al. 2014). Unfortunately clear evidence is not always present, especially in earlier or ephemeral sites, and even within modern foraging societies (Brooks and Yellen 1987; Mallol et al. 2007; Parker et al. 2016). Fire evidence in open-air sites, especially early sites, presents challenges in that natural wildfires may have affected remains, or that taphonomic processes may have degraded, removed or relocated materials. Although it can be challenging to incorporate innovative techniques, it is helpful when archaeologists determine types of artifacts or lines of evidence that more clearly associate human behavior (e.g., stone knapping) with prolonged, intense, heating – of the type of energy and duration provided by a campfire (Goldberg and Aldeias 2016; Mercieca 2000; Oestmo 2013). Establishing novel and quantitative methods linking human behavior and fire evidence (which otherwise may be equivocal with landscape fires) is critical to distinguishing evidence of human-controlled fires (Cutts et al. 2015, 2016; Goldberg and Aldeias 2016; Hlubik et al. 2017 *in press;* Sandgathe and Berna 2017, and other articles in that volume).

Likewise, descriptions of *fire-cracked rock* (FCR), and the related *fire-modified rock* (FMR), are widely used, but generally lack standardization or quantification (Graesch et al. 2014; Jackson 1998; Mercieca 2000; Ng 2004). In response, a number of studies have argued for, and provided, more systematic approaches to the study of FCR (House and Smith 1975; Jensen et al. 1999, Ng 2004, McDowell-Loudon 1983; Mercieca 2000, Oestmo 2013, Pagoulatos 1992 and Patterson 1995). For example, FCR may be termed whitened, blackened, reddened, cracked, crenulated, crenated, curvilinear, irregular, or shatter (among other terms; Jackson 1998; Latas 1992; McParland 1997; Ng 2004; Oestmo 2013; Patterson 1995; Purdy 1975; Purdy and Brooks

1971; Taggart 1981; Thoms 1986, 2008, 2009). All of these descriptions may be equivocated by natural processes (Blackwelder 1927; Shahack-Gross et al. 1997). “Shatter” and “spall” are terms often invoked in describing both the appearance and mechanical processes for how heat may affect stone (Mercieca 2000; Patterson 1995; Purdy 1975). These can be distinct from characteristics typical of knapped stone, having irregular, jagged, curvilinear forms, and possibly lacking signs of conchoidal fracture (e.g., platform, bulb of percussion, fissures and ripple marks, etc.; Mercieca 2000; Purdy 1975; Purdy and Brooks 1971). Fire-modified rock (FMR), somewhat distinct from FCR in that it should not show cracking or crazing (i.e., indicative of extreme heat damage), is more commonly applied to stony materials that have undergone some “engineering” (annealing) by humans, often in pursuit of improving the mechanical flakeability of the material. These may be inferred by color and luster changes, while corroboration may require petrographic or other techniques to verify (Brown et al. 2009; Schmidt et al. 2013). Research on this heat-treatment of stone is an area that exemplifies how systematic, quantifiable, experimental approaches to the study of fire’s effects on rock can be very effective in advancing archaeological knowledge (Brown et al. 2012; Delagnes et al. 2016; Domanksi and Webb 1992; Domanski, Webb and Boland 1994; Flenniken and Garrison 1975; Griffith et al. 1987; Joyce 1985; Rowney and White 1997; Schmidt et al. 2011; Schmidt et al. 2012; Schmidt et al. 2013). Heat-treated stone and FCR should not be taken as interchangeable, and we concur that clarification between what constitutes thermally-altered stone (TAS), fire-modified rock (FMR), fire-cracked rock (FCR), heat-treatment and the like continues to be important (Graesch et al. 2014; Jackson 1998; Mercieca 2000; Ng 2004). In this paper, we use the term FCR to apply to stony materials having undergone extreme thermal exposure (>550°C for 2 hours or more) and exhibiting cracking and fragmenting.

FCR is an artifact class represented by large quantities in many archaeological sites. Although there have been efforts to understand how fire affects stone, researchers have noted that FCR is often understudied or not treated seriously (Graesch et al. 2014; Jackson 1998; Nakazawa et al. 2009; Ng 2004; Mercieca 2000). Other researchers acknowledge that fire archaeology is a relatively undeveloped field that has struggled to embrace innovative methods (Goldberg and Aldeias 2016; Gowlett and Wrangham 2013). Over recent decades, archaeologists have come to view experimental work as a critical aspect and potentially important proxy to inform archaeological interpretations (Graesch et al. 2014; Jensen et al. 1999; McDowell-Loudon 1983; Mercieca 2000; Mercieca and Hiscock 2008; Pagoulatos 1992; Sandgathe and Berna 2017, and other articles in that volume; Schmidt et al. 2013). We include a broader review of what comprises evidence of human-controlled fire, what constitutes FCR, recent advances in the archaeology of fire, and early sites argued to present remains of human-controlled fire in Supplementary Materials, Appendix A, and references therein.

2.1.2 Introducing thermal curved-fragments

This paper describes a particular fragment type, and presents actualistic and archaeological data that associates discrete, long-duration, high-energy fire events (i.e., campfires) and human behavior. We label this artifact type as *thermal curved-fragments* (hereafter, TCF). Our analysis provides the morphological distinctions of TCFs relative to other forms that may be found in archaeological assemblages. We do not stipulate the likely frequency of these forms in assemblages exposed to campfires, but suggest that TCFs can appear in a variety of tool stone. It is important to note that what we are describing as TCFs are *not* meant to infer intentional treatment of stone; rather we suspect that most TCFs are incidental by-products of the association of knapped materials with campfires.

TCFs are a highly symmetrical form of lithic artifact. In many cases they may have been typed as a common angular fragment, and share generalized characteristics with them. For example, angular fragments may not exhibit all typical effects of conchoidal fracture (sometimes not showing all the useful diagnostic indicators like platform, bulb of percussion, tapered edge, ripple marks, fissures, etc.; Isaac and Harris 1997). TCFs typically do not show *any* of these classic features of conchoidal fracture, and are further distinguished by not typically exhibiting cortical surface (which may be present on angular fragments). Angular fragments are common in knapping debitage, but also may be produced by trampling, snapping, and diagenetic processes such as freezing, solarization, weathering, and rockfall.

Experiments in this study test how fire affects a variety of rock common in archaeological sites found in the Koobi Fora Formation (Isaac 1997) and used in tool production (see Table 1). Tests include campfires as well as simulated natural landscape fires conducted by the USDA Forest Service on locations in the southeastern United States (using lithic materials from East Africa and the US). We also examine the impact of natural weathering (e.g., solarization) on these same materials. We present here an initial analysis and discussion of the TCF type.

As a preliminary indication of the possible impact of fire on archaeological assemblages, we reviewed stone artifacts from archaeological sites from the Koobi Fora Formation (~1.6Ma). We incorporate these archaeological materials into this analysis and compare them to the assemblage of experimentally produced TCFs, experimentally produced knapping debitage, and natural exfoliations collected from similar materials exposed on outcrops in the Koobi Fora region. We incorporate material from both the Okote Member (~1.6 Ma) and Upper Burgi Member (~2.0-1.87 Ma). The FxJj20 Sites Complex, on the Karari Ridge, Koobi Fora

Formation, has yielded evidence that has been argued as potential hominin-controlled fire. While debated, the evidence includes basalt pot-lid fragments, highly localized circular rubified sediment “patches”, paleomagnetic and thermoremanent signatures indicating some heating had occurred in these reddened sediments as well as Developed Oldowan artifacts suggesting asscociated hominin activity (Bellomo 1994; Harris 1978, 1997; Hlubik et al. 2017; Rowlett 2000).

We provide data from these two time periods to test the assertion that older assemblages should show no evidence of the intersection of ground level fires and knapped stone (i.e., TCFs), while assemblages from the later time period may reflect early instances where hominins had some control over these campfires. This study investigates whether TCFs can be quantified as distinct from unfired debitage created by knapping and natural exfoliations, and test whether they are a product of discrete, high-energy, long-duration campfire events.

2.2 Methods

2.2.1 Lithic Materials, Fires, and Fuels

We procured most raw lithic materials from the modern landscape in the region surrounding Sibiloi National Park, Marsabit District, Kenya. These included basalt and ignimbrite sources on the Karari Ridge and basalt, chalcedony, chert and ignimbrite from Il Eriet Laga in Ileret, Kenya (Table 1). All knapping was conducted with appropriate Early Stone Age (ESA) technologies (e.g., hard hammer free-hand; no modern hammers, no copper billets or pressure flakers, etc.). Knapping aimed to produce large, useful flakes in accordance with processes that result in forms associated with Oldowan “choppers”, “scrapers” and Acheulean

"hand-axes" according to methods described in previous experimental work (Toth 1982, 1987; Braun et al. 2006).

Table 1. List of material types used in this study. The variety does not indicate quantity of each material, as flakes, represented in the study (refer to Table 2). For example, while many basalt flakes from multiple basalt cobbles were utilized, here is listed the general type, source location, and macroscopic assessment of color before and after heating.

Material	Description	Source Location	Munsell color (raw)	Munsell color (heated above 550°)
Basalt	Grey/black; coarse grained with small crystal inclusions	Areas 11, 5 and 131, Ileret and Karari, Kenya	GLEY1 2.5/N	White to 2.5YR 4/6
Chalcedony: translucent brown	"Jasper"/chert type; caramel colored; fine-grained homogenous	Il-Eriet Laga, Area 11, Ileret, Kenya	7.5YR 4/6	10R 8/1
Chalcedony: grey	Blended translucent and opaque grey; fine-grained, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	GLEY2 8/10B	10YR 8/1
Chalcedony: mottled pink/white/brown	"Chert" type; mottled colors pink, white, caramel, dk brown, beige, dk grey; fine-grain, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	10R 8/2; 2.5YR 2.5/1; 5YR 5/6; 5YR 3/4; white	2.5YR 7/3, 7/1
Chalcedony: mottled purple/brown/grey	Chert type; lightly mottled purple, purple-brown, dk grey; fine-grained, glassy	Area 5, Ileret, Kenya	10R 2.5/1	7.5YR 6/2

Chalcedony: pink/beige	Chert type; pinkish-beige with black speckling and spidery line; fine-grained	Il-Eriet Laga, Area 11, Ileret, Kenya	7.5YR 7/3	White (opaque)
Chalcedony: translucent blue	Pale blue translucent; very fine-grained homogenous, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	GLEY2 8/10B	White to GLEY2 8/10B
Chalcedony: translucent grey	Translucent grey w/ minute black speckles; fine-grained, homogenous	Area 5, Ileret, Kenya	GLEY2 7/5PB	white
Chalcedony: translucent grey/green	Mottled grey-green-yellow; homogenous, extremely fine-grained, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	2.5Y 8/1, 8/2, 7/1	2.5YR 4/8
Chalcedony: yellow	Chert type yellow with quartzite inclusions; medium grained	Il-Eriet Laga, Area 11, Ileret, Kenya	10YR 4/4; 10YR 8/1	10R 8/3
Chalcedony: black/brown	Chert type ‘tiger eye’ appearance; swirled bands of caramel in black, w/ white flecks; coarse grained	Il-Eriet Laga, Area 11, Ileret, Kenya	10YR 5/6; GLEY 2.5/N; 10R 8/1	Black GLEY 2 2.5/N
Chalcedony: brown	Chert type; brown caramel; fine-grained, homogenous, glassy	Flint River, Albany, Georgia, USA	5YR 5/6	5RP 6/2; 10YR 8/6
Chalcedony: grey	Novaculite type; gray banding; fine-grained,	Arkansas, USA	5Y 7/2	5Y 6/2; 5BG 7/2

	homogenous, glassy			
Ignimbrite: pink	Red/pink; coarse grained with crystal fragments	Area 11, Ileret, Kenya	10R 6/6	GLEY1 5/10Y
Ignimbrite: green	Green/gray; coarse grained with crystal inclusions	Areas 11, 131, Ileret and Karari, Kenya	GLEY1 6/10GY	GLEY 1 2.5N
Quartzite	White; coarse grained	Area 11, Ileret, Kenya	White; very light gray 8.5N	10R 7/1

Here we use the term campfire to describe highly localized, high-heat, and long duration (>2 hours) and compact *ground level* (<75 cm. above ground surface) fire (Cutts et al. 2015). Fuel for experimental campfires was gathered in the Sibiloi National Park region. Grasses were used for tinder and *Acacia spp.* for wood. These materials are similar to what may have been available throughout this area for the past 1.5 million years (Bamford 2011, 2017). Although we do not imply that ESA fires, should they have been controlled by hominins, were manufactured (rather than scavenged from landscape wildfires), our fire ignition(s) utilized the traditional hand-drill technique (local Kenyan materials; *Acacia spp.* root hearthboard and *Conzya spp.* drill; Cutts 2004).

Knapped lithic materials used in fire events were selected for broad similarity of size (ca. 3.5cm -6cm max length, with clear platforms, bulbs of percussion, fissures and ripple marks all indicative of conchoidal fracture). Unknapped materials chosen for fire events conformed to roughly 10-20cm max length cobbles common to river- or streambank and outcrop regions (Toth 1987, Braun et al. 2008). Lithic materials were documented prior to exposure in firing experiments.

Areas used for experimental fire events were swept clean of debris prior to laying the fire and arranging lithic materials for heat exposure. Post-ignition, fires were monitored and temperatures recorded periodically (every five minutes early in event, and every 10 minutes after peak temperature was reached) using a laser infrared (IR) thermometer (Sper Scientific 800103) for approximately three hours. Temperatures were measured in the central aspect of the fire, above the ember pile. Each fire exceeded 550°C within 5-10 minutes of ignition, and remained above this temperature for 2.0 hours or more. Fires were allowed to cool for at least 24 hours prior to excavation and recovery of burned lithic materials.

In total, 39 separate fire events were conducted incorporating more than 800 flakes, 50 unworked cobbles, and 40 naturally-weathered exfoliations (refer to Table 2). Initially, fire events mixed materials; however, once we noted the potential TCF morphology, subsequent events kept materials in distinct association: fires with unknapped cobbles, for example, likely would not include flaked tools (and *vice versa*). In efforts to determine any TCF-tendencies of different stone, fires with flakes often included only one type of material (e.g., basalt or chalcedony, etc.). Some events approximated "natural" settings (e.g., cobbles partially buried), while others approximated a fire laid on a lithic scatter or flakes falling into an existent campfire. Germane to fire studies, some of our events also included bone.

Table 2. List of experimental fire events in this study.

No.	Event	Date	Materials	Condition
1	2013.F-1	6.28.13	chalcedony/chert, quartzite, basalt, bovid bone humerus/vert	flakes (12), cobble (basalt); stage 3 weathering (bone)
2	2013.F-2	6.29.13	basalt, ignimbrite	cobbles (4, round)
3	2013.F-3	6.30.13	chalcedony, ignimbrite	flakes (10)

4	2013.F-4	6.30.13	chalcedony/chert, ignimbrite, basalt	cobbles (5, round)
5	2013.F-5	7.1.13	basalt, chalcedony/chert, ignimbrite	flakes (~12)
6	2013.F-6	7.2.13	basalt, chalcedony/chert, ignimbrite	flakes (168)
7	2013.F-7	7.2.13	basalt, chalcedony/chert, ignimbrite, quartzite	cobbles (8, round, partially buried)
8	2013.F-8	7.5.13	basalt, ignimbrite	cobbles (2, round)
9	2013.F-9	7.5.13	bone (shoat scapulae, humeri, tibiae)	fresh
10	2013.F-10	7.6.13	chalcedony/chert, ignimbrite	flakes (unknown #, as knapper-debitage)
11	2013.F-11	10.26.13	chalcedony/chert (N. Amer.)	flakes (20)
12	2014.F-1	6.28.14	chalcedony/chert	flakes (16), core (1, buried 3cm)
13	2014.F-2	6.28.14	ignimbrite	flakes (15), core (1, buried 3cm)
14	2014.F-3	6.29.14	chalcedony/chert	flakes (15) lost to flood
15	2014.F-4	6.30.14	ignimbrite	flakes (15) lost to flood
16	2014.F-5	7.3.14	basalt	flakes (15)
17	2014.F-6	7.4.14	chalcedony/chert	flakes (15)
18	2014.F-7	7.4.14	chalcedony/chert	flakes (15)
19	2014.F-8	7.7.14	basalt, chalcedony/chert, ignimbrite	cobbles (13, round)
20	2014.F-9	7.7.14	chalcedony/chert, ignimbrite	flakes (15; into cooling fire <350°)
21	2014.F-10	7.13.14	chalcedony/chert	flakes (15)
22	2014.F-11	7.13.14	ignimbrite	flakes (15)
23	2014.F-12	7.13.14	chalcedony/chert (“jasper”)	flakes (15)
24	2014.F-13	7.14.14	basalt, chalcedony/chert, ignimbrite, quartzite	cobbles (14, flat, angular)
25	2015.F-1	6.28.15	basalt, chalcedony/chert, ignimbrite, bone (shoat scapulae)	flakes (20), fresh (bone)
26	2015.F-2	7.12.15	basalt, chalcedony/chert, ignimbrite	flakes (150)
27	2015.F-3	7.12.15	basalt, chalcedony/chert, ignimbrite	cobbles (5, round)
28	2015.F-4	7.14.15	basalt, chalcedony/chert	flakes (20) weathered exfoliations (20, basalt)
29	2015.F-5	7.14.15	basalt, chalcedony/chert	flakes (20), soaked weathered exfoliations (20, basalt)
30	2016.F-1	6.29.16	chalcedony/chert	flakes (15)
31	2016.F-2	7.4.16	basalt	flakes (15)

32	2016.F-3	7.4.16	chalcedony/chert, basalt	flakes (20), hand-axe (replica, basalt)
33	2016.F-4	7.10.16	chalcedony, basalt	flakes (~15)
34	2016.F-5	7.11.16	ignimbrite	flakes (15)
35	2016.F-6	7.11.16	ignimbrite	flakes (15)
36	2016.F-7	7.11.16	chalcedony/chert	flakes (15)
37	2016.F-8	7.12.16	basalt	flakes (15)
38	2016.F-9	7.12.16	chalcedony/chert	flakes (15)
39	2016.F-10	10.15.16	chalcedony/chert (N. Amer.)	flakes (25)

2.2.2 Fire Excavation Methods

When fires cooled to ambient, unexhausted fuel was removed and large (> 2cm) lithic pieces recovered. Excavations used brushes, dustpans and fine-mesh screens (2mm) to retrieve lithic material and shatter. After collection, fire cracked pieces were sorted into groups: large cracked FCR, TCFs, slivers/shatter and unbroken material. This included all through-cracked sections from cobbles.

2.2.3 Measurement and Statistics

In addition to the pieces collected from fires, 500 unfired debitage pieces were selected using a random number table from an assemblage of over 4000 fragments produced during the knapping of materials that are frequently recovered from archaeological assemblages in the Koobi Fora Formation (e.g. basalt, chalcedony, ignimbrite). No specific size criteria (e.g., max length) was used to exclude unheated debitage from the sample. Surface collections from outcrops of the Koobi Fora Formation in the Ileret and Karari Ridge regions recovered 45 natural exfoliations (weathered stone fragments) exhibiting curvilinear characteristics (note: these were measured as described according to study parameters, prior to some being used in subsequent fire experiments). All pieces were measured using the same twelve (12) variables: 1) total length (TL), 2) curve height (CH), and 3-12) width and thickness at each end (A, B), as well as quarter-

and mid-points (¼, ½, ¾) (Figure 1). When applied to pieces (i.e., debitage) drastically differing from a curvilinear shape, TL was measured as the maximum dimension and the largest flat surface was chosen as the top (of the "curve") with the remainder of the measurements applied based on that orientation. We used the standard deviations (SD) of the multiple thickness and width measurements within each piece as an indicator of evenness (or, "Evenness Quotient", EQ) of width and thickness along the length of the curve. Kruskal-Wallis tests compared the morphological variables of pieces classified as TCFs to those of the randomly selected debitage (i.e., from knapping), natural exfoliations and archaeological samples. F-tests compared the level of evenness as variance from the means by class. Principal Components Analysis attempted to visualize which characteristics account for the variability between these populations. Variables included in the Principal Components Analysis were the EQ (SD of thickness and width along length), as well as total length (TL) and adjusted curve height (CH). Using Figure 1 for reference, measurements to calculate curve height (CH) and curvature angle (angle length, angle depth and thickness at mid-point, followed by Euclidian geometry; Andrefsky 1986) were based on the plane provided by TL (using lower caliper jaw or straight-edge), to the top of mid-point, then subtracting the thickness value of the mid-point (Thickness at ½). These measures of EQ were used to emphasize relative measures of shape, as opposed to overall size, which varied within the samples.

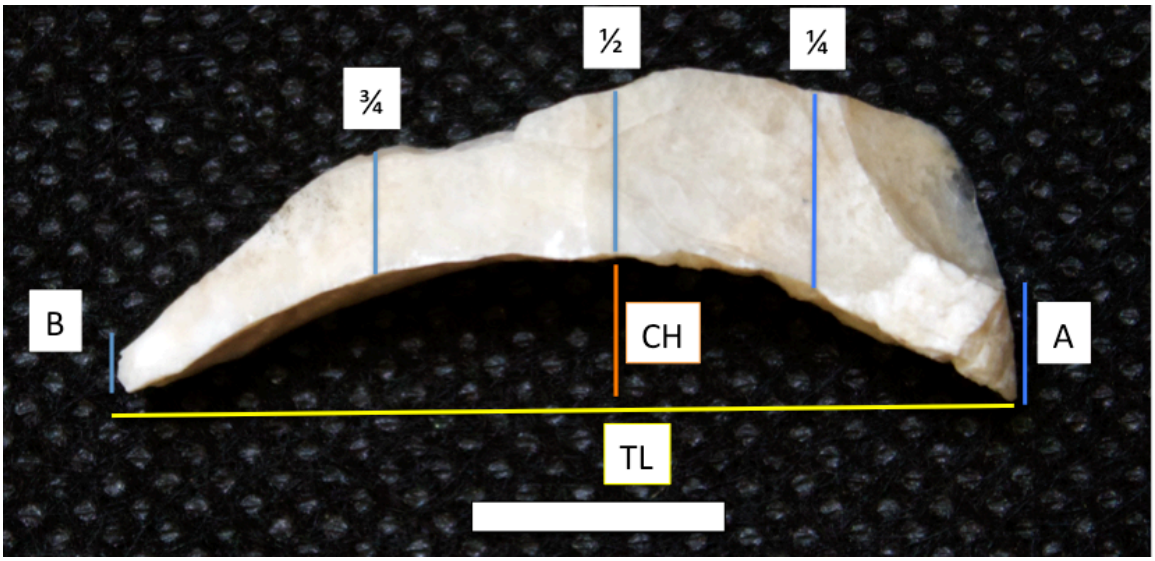

Figure 1. Experimentally produced chalcedony TCF showing twelve (12) measurement points: 1) total length (TL); 2) curve height (CH); 3-12) width and thickness at each end (A, B), and quarter-, mid-points (¼, ½, ¾). Scale = 1cm.

2.2.4 Archaeological Specimens and Laboratory Analysis

Collections from the 1970s excavations at the FxJj20 sites complex (including –Main, -East and –AB) are currently housed at the National Museums of Kenya. Assuming that potential TCFs—should they be present in these collections—would in all likelihood have been described as "angular fragments", a review of FxJj20 collections focused on this class of artifact. More than 1500 artifacts from these collections are termed angular fragments. Fourteen potential TCFs have been preliminarily identified from the FxJj20 collections. Additionally, three other TCF-similar archaeological pieces were included; one is from ongoing excavations at the new rubified feature FxJj20Main-Extension-0, one is from surface collection from a recently discovered rubified feature in Area 131, Okote Member; one is from ongoing excavations at FxJj20AB (Hlubik et al. 2017). These were measured in accordance with the protocol described above.

Furthermore, a random sampling (n=21) of the angular fragment assemblage from FwJj20 was included in this analysis. The site of FwJj 20 is well dated to 1.95 Ma and includes thousands of stone artifacts as well as bones that bear evidence of butchery (Braun et al. 2010).

Analyses of the variance in the measurements described above were conducted in the statistical software R (Version 3.5; RCoreTeam 2013). Due to the non-parametric nature of many of the measurements in this study we chose to use the Kruskall-Wallis rank sum test to measure variance across assemblages. Post-hoc tests were then used to measures significant differences between specific fragment types (e.g. TCF, naturally exfoliated fragments). A compiled database of measured lithic material is available in the Supplementary Materials (Appendix B). These include the 500 pieces of knapped debitage, 45 natural exfoliations, 192 experimental TCFs, and 17 archaeological specimens from the FxJj 20 site complex, and the 21 angular fragments from FwJj20.

We use a linear discriminant function (R package MASS) to identify differences between fragment types using multiple variables. Four shape variables were used in the discriminant function because this seemed to discriminate the groups most accurately. Discriminant functions were developed using a training set of the experimental assemblage, which included experimentally produced TCFs, naturally exfoliated fragments and angular fragments from knapping experiments. The “leave one out” method was applied, where the classification of a specific fragment is based upon a model that was developed without that specific fragment. The success rate of the discriminant function is based on the ability of the function to accurately assign a fragment to a particular class.

2.2.5 USDA Forest Service natural landscape fires over lithics "scatters"

The USDA Forest Service Southern research conducts controlled (or, prescribed) burns of various habitats in and around national forest in the United States. To simulate the impact of wildfires on stone artifacts, and to test whether TCFs might be generated by ground-level heat of landscape fires, we placed experimental stone flakes in regions that were designated for such burning. These areas are largely hardwood and pine forests, along with grasslands, and as such fires tend to be crown and surface fires (Scott et al. 2014). These different types of fires result in different durations and temperatures. A series of flakes – again, selected to represent useful tool flakes ca. 5-6cm max length – made from the same materials (e.g. basalt, chalcedony, and ignimbrite) used in experiments in Kenya, as well as North American materials (chert and novaculite), were placed at locations where the fire front would pass directly over the artifacts. One hundred (100) flakes were subjected to five (5) surface burns over the course of five (5) days. The flakes were recovered after the landscape fire had passed and cooled, and inspected for heat-induced modifications.

2.3 Results

2.3.1 Do unknapped cobbles yield TCFs when burned?

Fragments that conform to the morphological description of TCFs were not recovered from unknapped materials (cobbles n = 52) that were burned. Occasionally a fragment would detach, yielding a "pot-lid" (showing cortical and ventral – interior – surface) or, possibly resembling a natural exfoliation. Measurements of these fragments indicate they do not exhibit the evenness quotient (EQ) of TCFs, and are distinguishable from them. Fragments created from burned, unknapped cobbles are broader and have more rounded ends than TCFs. The fragments produced from exposing cobbles to fires also exhibited—unlike TCFs—a cortical dorsal surface

(see Figure 2). These “pot-lid” fragments do not exhibit four distinct sides, as are typical of TCFs.

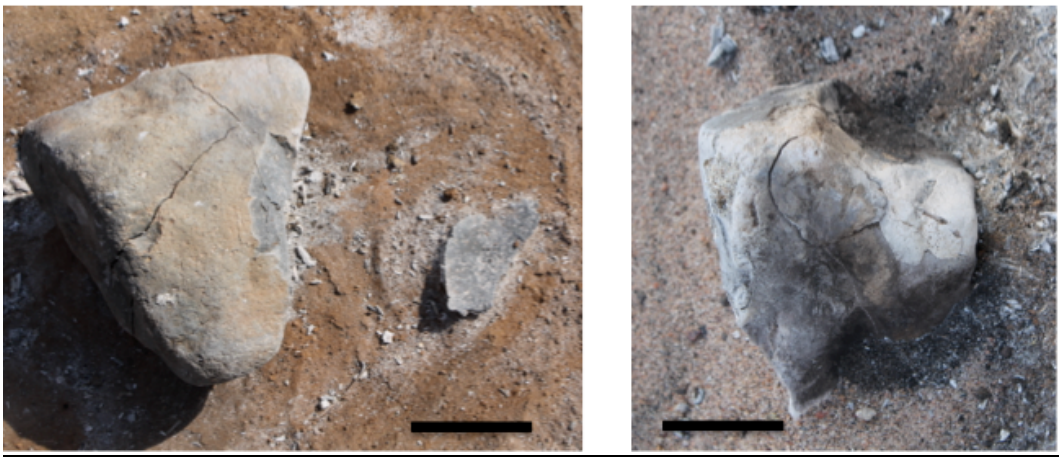

Figure 2. Examples of heat-modified, but unknapped, cobbles. Pot-lid fractures typically show cortical surface, a flattened ventral surface, but without four distinct sides. Scales = 5cm.

2.3.2 Are natural exfoliations like TCFs?

Natural exfoliated fragments do not exhibit a “flattened” or “lid” appearance (reduced thickness from the ventral to dorsal surfaces) that pot-lid heat fractures demonstrate. Natural exfoliations exhibit a more “onion-skin” peeling quality that appears superficially similar to TCFs (Figure 3). However, natural exfoliations are statistically distinct from TCFs (Figures 5-9; Table 3). When subsequently fired (*after* initial measurements for study comparison), neither the natural exfoliations nor their parent materials yielded TCFs. If any further degradation occurs, naturally exfoliated fragments exhibit cracking, crumbling, and friability similar to that exhibited by cobbles exposed to fires.

Figure 3. Natural exfoliations (basalt) from weathering. Distinct from pot-lids, exfoliations tend to exhibit a "peeling" aspect (where pot-lids tend to have a flattened ventral surface). Although generally curvilinear, such exfoliations do not have four distinct sides; they are statistically distinct from TCFs. Scales = 5cm.

2.3.3 TCFs are produced from intensely heated flakes, bifaces and cores

Typical TCFs have a curvature angle (following Andrefsky 1986) falling between 170° and 177°, with 67% falling between 173°-176°. TCFs do not have characteristic ventral and dorsal surfaces because they do not exhibit the typical fracture patterns (e.g., platform, bulb, tapered edge, etc.) associated with conchoidal fracture seen in knapped stone. However, TCFs do usually exhibit one surface that is more concave. This concave surface is referred to as the "ventral" surface of TCFs. The surface that parallels this "ventral" surface but is not concave we refer to as the "dorsal" surface. The dorsal, ventral and lateral surfaces of TCFs are typically smooth and free of cortex (Figures 1 and 4). TCFs exhibit notable symmetry, being narrow in width and thickness relative to length, and (typically) have four surfaces (dorsal, ventral and 2 lateral sides). TCFs do not exhibit a platform, bulb of percussion or termination (feather) edge. They often display tapered points on each end, or a point on one end and a truncated taper at the other end (refer to Figure 4). Pieces classified as partial TCFs fit many, but not necessarily all, of

these TCF characteristics. For example, some partial TCFs have three, rather than four, surfaces, and may resemble the more generally termed “heat-shatter”. Shatter slivers fit several of the classic TCF characteristics but are less curvilinear and are typically narrower relative to their length, and much smaller (i.e, <1cm).

Figure 4. An assortment of experimental TCFs. Materials include basalt, chalcedony/chert, and ignimbrite. Middle row, in particular, demonstrate the type. Scale = 2cm.

Kruskal-Wallis tests comparing the distributions of distinctive variables (evenness of thickness, evenness of width; and adjusted curvature height) between groups shows that the experimental TCF group is statistically different from unfired debitage and natural exfoliations (Figure 5; Table 3). However, it should be noted that no such statistical differences exist between the experimentally produced TCF assemblage and the materials selected from the FxJj 20 collection that were identified as possible TCFs.

Table 3: Statistical analyses of comparisons of measurements among different fragments types.

Evenness of Thickness

Kruskal-Wallis Chi2= 59.2189, df = 4, p <.001

Dunn's test Pairwise post-hoc tests (Bonferroni correction)

Comparison	Z statistic	p- value
Archaeological - Experimental Debitage	-2.31	0.10
Archaeological - FwJj20	-1.04	1
Experimental Debitage - FwJj20	0.90	1
Archaeological - Natural Exfoliation	-2.77	0.02
Experimental Debitage - Natural Exfoliation	-1.40	0.79
FwJj20 - Natural Exfoliation	-1.58	0.56
Archaeological - TCF	0.24	1
Experimental Debitage - TCF	7.06	<0.01*
FwJj20 - TCF	1.67	0.46
Natural Exfoliation - TCF	4.94	<0.01*

Evenness of Width

Kruskal-Wallis Chi2 = 331.7571, df = 4, p-value <.001

Dunn's test Pairwise post-hoc tests (Bonferroni correction)

Comparison	Z statistic	p- value
Archaeological - Experimental Debitage	-6.83	<0.01*
Archaeological - FwJj20	-4.29	<0.01*
Experimental Debitage - FwJj20	0.97	1
Archaeological - Natural Exfoliation	-5.55	<0.01*
Experimental Debitage - Natural Exfoliation	0.49	1
FwJj20 - Natural Exfoliation	-0.53	1
Archaeological - TCF	-0.53	1

Experimental Debitage - TCF	17.29	<0.01*
FwJj20 - TCF	5.30	<0.01*
Natural Exfoliation - TCF	8.40	<0.01*

Total Length

Kruskal-Wallis Chi2 = 279.857, df = 4, p-value <.001

Dunn's test Pairwise post-hoc tests (Bonferroni correction)

Comparison	Z statistic	p- value
Archaeological - Experimental Debitage	-6.14	<0.01*
Archaeological - FwJj20	-1.97	0.24
Experimental Debitage - FwJj20	3.52	<0.05*
Archaeological - Natural Exfoliation	-6.20	<0.01*
Experimental Debitage - Natural Exfoliation	-1.67	0.46
FwJj20 - Natural Exfoliation	-3.96	<0.01*
Archaeological - TCF	-0.54	1
Experimental Debitage - TCF	15.38	<0.01*
FwJj20 - TCF	2.13	0.16
Natural Exfoliation - TCF	9.46	<0.01*

Curvature Height

Kruskal-Wallis Chi2 = 41.1102, df = 4, p <.001

Dunn's test Pairwise post-hoc tests (Bonferroni correction)

Comparison	Z statistic	p- value
Archaeological - Experimental Debitage	2.96	<0.05*
Archaeological - FwJj20	5.74	<0.01*
Experimental Debitage - FwJj20	5.02	<0.01*
Archaeological - Natural Exfoliation	3.20	<0.01*
Experimental Debitage - Natural Exfoliation	1.17	1

FwJj20 - Natural Exfoliation	-3.58	<0.01*
Archaeological - TCF	3.76	<0.01*
Experimental Debitage - TCF	2.49	0.06
FwJj20 - TCF	-3.97	<0.01*
Natural Exfoliation - TCF	0.17	1

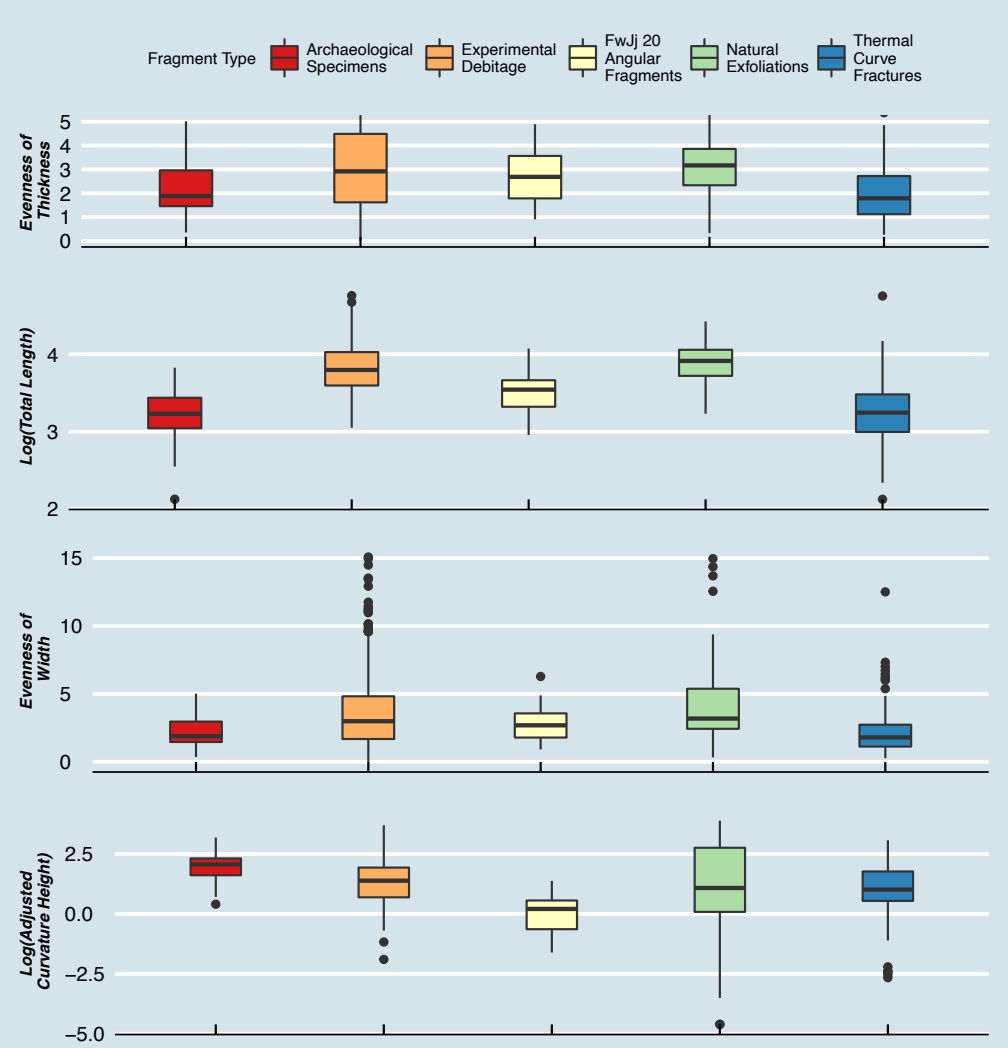

Figure 5: Box-plot of measurements of different fragment types. Comparison of several different measurements. This comparison includes all fragment types including natural exfoliations (n=45); debitage produced during knapping (that was not exposed to fire; n= 500); angular

fragments from the 1.95 Ma assemblage of FwJj 20 (n=21); TCFs produced during experimental fires (n=192); and suspected TCFs from the 1.5 Ma assemblage at FxJj 20 (n=17). None of these data sets fit the assumption of a normally distributed data set. See statistical comparisons between groups in Table 3.

The discriminant function was able to correctly identify the class of object 84.2% of the time. TCFs can be distinguished from other fragments 78% of the time. Debitage fragments were correctly identified by the discriminant function 93% of the time. Naturally exfoliated pieces were not distinguished quite as well because they overlap substantially with experimental debitage (naturally exfoliated fragments were only correctly classified in 13.3% of cases). Although there is substantial overlap between groups in the classification of the experimentally produced pieces (Figure 6), experimentally produced TCFs show a very low probability of classification as either knapping debitage or naturally exfoliated fragments.

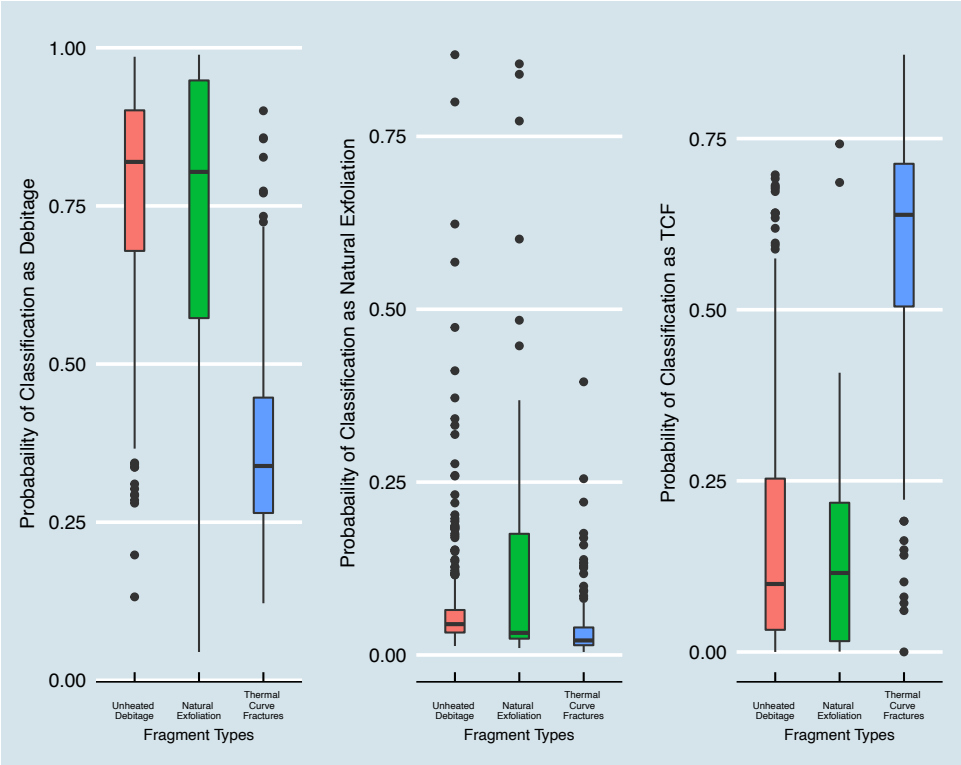

Figure 6: Probability of classification based on "leave-one-out" discriminant function analysis. Note that the experimentally derived TCFs show a very low probability of being classified as either experimental debitage or natural exfoliation. Naturally exfoliated pieces are not distinguished easily because of their overlap with the experimental knapping debitage.

When the discriminant function is applied to specimens of unknown classification (i.e. archaeological specimens) the resultant discriminant function scores reinforce the patterns seen previously in the individual measurements. The fragments identified as angular fragments from the FwJj 20 assemblage (1.95 Ma) are classified with experimentally produced debitage. In addition, the 17 fragments that were identified visually as potential TCFs are consistently (>60% of fragments) classified as TCFs (Figure 7). Furthermore, a density plot of the first linear discriminant function (93.5% of variance in the sample) indicates that both experimental TCFs and the archaeological specimens from the site of FxJj 20 have the lowest discriminant function scores and are distinct from the other fragment types (Figure 8).

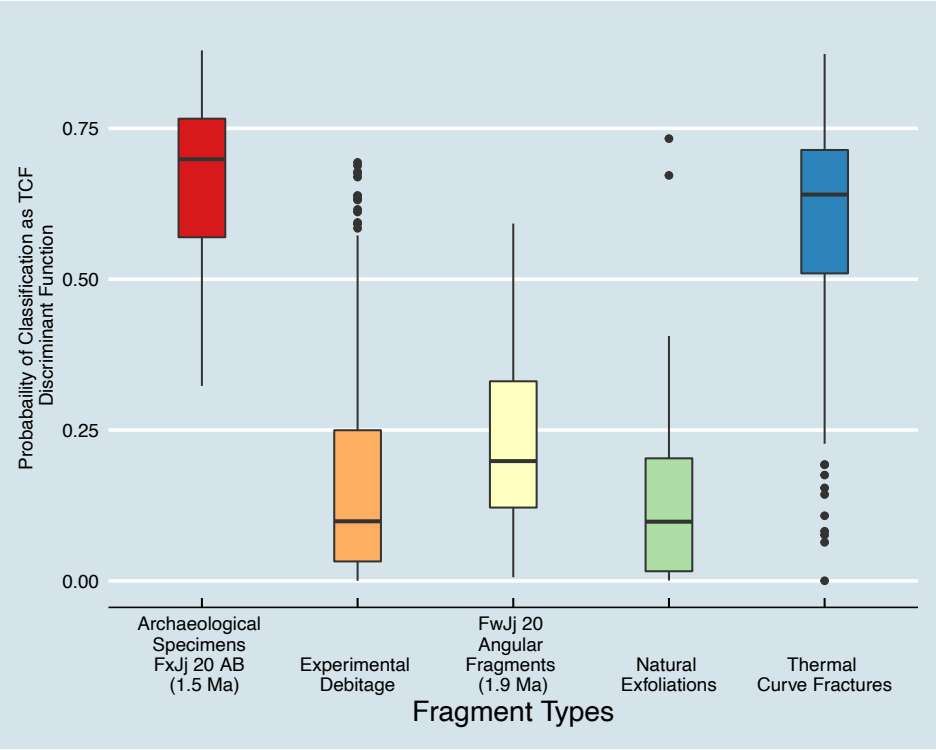

Figure 7: Probability of classification using Linear Discriminant function analysis. This discriminant function uses four predictor variables (Evenness of thickness, evenness of width, total length and adjusted curvature height.

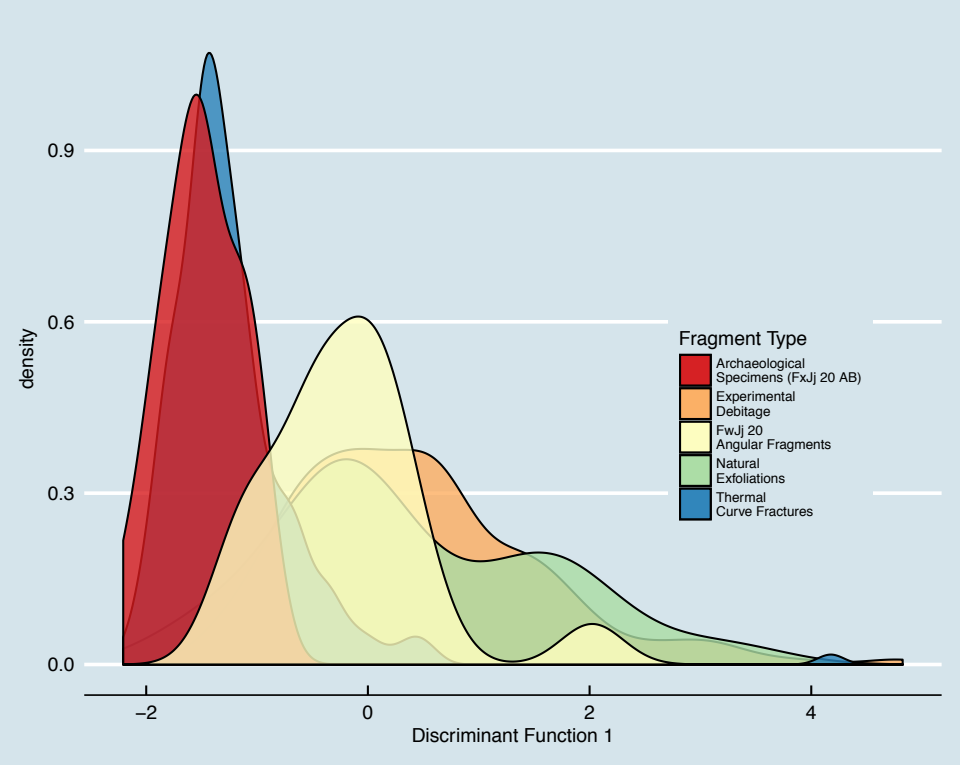

Figure 8: Density plot of the first linear discriminant function (93.5% of the total variance in the dataset). This linear discriminant function includes the four linear measurements of fragment shape. Archaeological specimens from the FxJj 20 sites and experimental TCFs have the lowest discriminant function scores of any of the fragment types.

Our principle components analysis (Figure 9) produced a solution with two principle components explaining greater than 90% of the variation between the experimental TCFs (n=192) and natural exfoliations (n=45), debitage (n=500), angular fragments from FwJj20 (Upper Burgi ca. 1.95mya; n=21) and archaeological “potential” TCFs from FxJj20 (n=17). In all cases, PC1 was primarily driven by the total length of the samples while PC2 was driven by a combination of adjusted curve height and the standard deviation of width. These analyses

suggest that the combination of these variables are the most appropriate characteristics for distinguishing TCFs from other forms of lithics in the archaeological record.

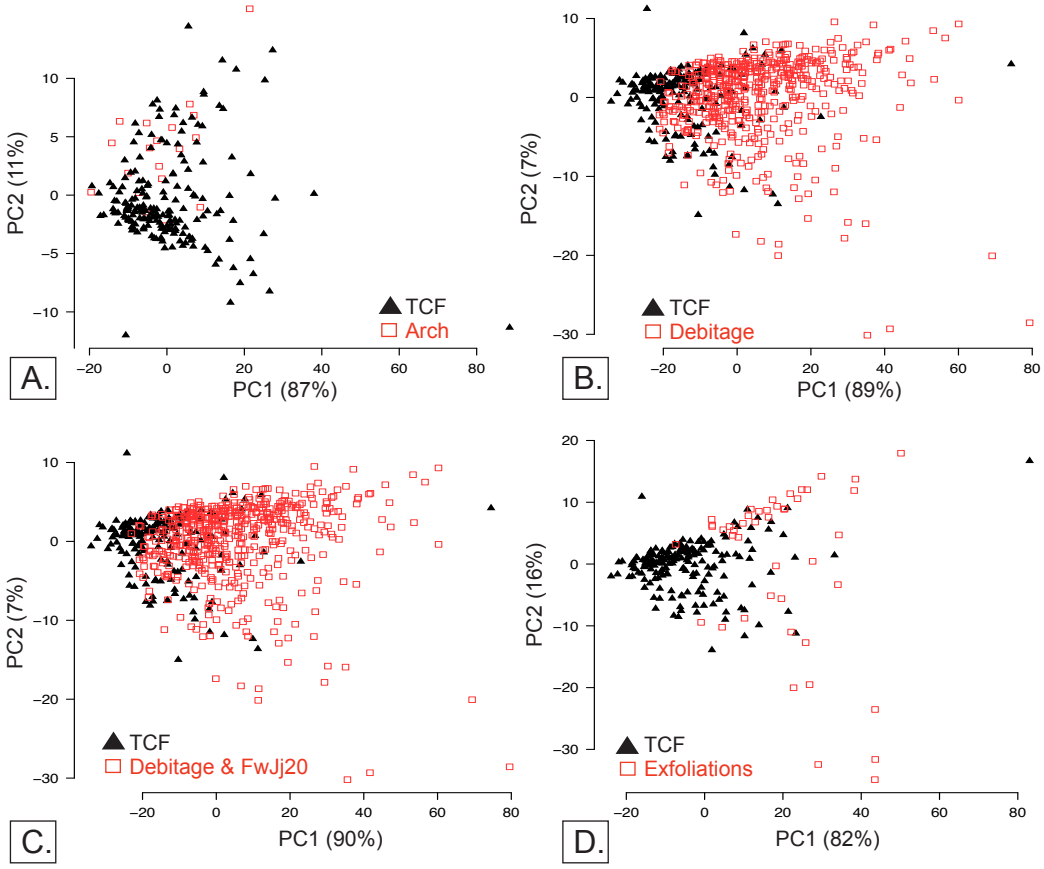

Figure 9. Plots of Principle Components Analysis comparing Evenness Quotient (SD width and SD thickness along the piece), TL (max length) and CH (curvature height) between experimental TCFs (n=192) and A) archaeological "potential" TCFs (Arch) from FxJj20 (Okote ca. 1.5mya; n=17), B) debitage (n=500), C) debitage (n=500), and angular fragments from FwJj20 (Upper Burgi ca. 1.95mya; n=21), and D) natural exfoliations (n=45).

2.3.4 Are TCFs produced on flakes exposed to landscape fires?

One hundred flakes, from Kenyan and American materials already described in this study, were subjected to five surface burns over the course of five days. Some (~30) of these flakes exhibited minor evidence of burning (e.g. color changes, "crazing" such as micro-cracks

in surface luster, and micro pot-lidding). Despite these indicators of burning, not a single TCF was produced during these USDA burns.

2.4 Discussion

2.4.1 TCFs: definition, why they exhibit symmetry, and possible fracture dynamics

A review of our dataset indicates that, broadly, TCFs are angular fragments with no clear directional indicators (e.g., platform, bulb of percussion), and no clear remnant marks of conchoidal fracture (e.g., ripple marks, feathered-edge). TCFs tend to be four-sided (occasionally three), with two tapered ends (or one taper and one truncate). TCFs have a curvature angle usually falling between 170°-177°, with most falling between 173° and 176°. Notably, when thickness and width measurements are calculated at five points along the length (each end, mid- and quarter-points), the standard deviations of these calculations (for thickness *and* width) will typically be very low (1-5 points). In our experimental TCF dataset, 97.5% of SD width and 97% of SD thickness fell (at-or-) below six points, with 98.5% exhibiting that trend in at least width or thickness. It is this last characteristic (Evenness Quotient of SD thickness *and* SD width) that, relative to total length, marks the recognizable symmetry of TCFs. The above definition rests on a constellation of attributes that, when taken as a whole, would suggest the presence of a TCF.

Although there are exceptions, most debitage and unfired angular fragments (and natural exfoliations) do not exhibit this extreme symmetry in thickness *and* width all along the length of the piece. Whereas the broad, catch-all, category of ‘angular fragments’ may be byproducts of knapping, trampling, snapping or through diagenetic processes (e.g., freezing, exfoliation, rockfall shatter), our experiments indicate that TCFs are not be produced in any of those processes. Results indicate that TCFs result from *knapped* stone that is subsequently exposed to high temperature, long duration fires – commensurate with human campfires. The specific

features of TCFs are not produced when unknapped stone (i.e., natural cobbles or boulders) fracture when exposed to fire. In addition, natural weathering or exfoliation does not produce these diagnostic patterns. Thermal curved-fracturing—a TCF—occurs when knapped materials (especially flakes, but including bifaces and cores) are exposed to high-heat, long-duration, high-energy ground-level fire events (i.e., exceeding 550°C for 2 or more hours). This is possibly due to characteristics common to knapped materials, but that are absent in unknapped materials. The particular features of conchoidal fracture— ripples marks, Hertzian cone, bulb of percussion, etc. (Cotterell and Kaminga 1992) and the tendency for knapped flakes to be asymmetrical—appear to cause knapped materials to form TCFs as a distinct heat-expansion event. For example (and testable as hypotheses) tool flakes are asymmetrical in terms of mass. The bulb of percussion is thicker and the tapering terminal edge is very thin, yielding a thermal situation where the edge heats more rapidly than the bulb. The subsequent heat-expansion fracture occurs along this differential zone (Figure 10), and appears inverse to the direction of the ripple marks. TCF symmetry seems to stem from the tendency for a flake (the parent piece prior to heating) to exhibit less variability in thickness across the width; what are originally the dorsal and ventral surfaces of the flake become the sides of a TCF. The tapering "ends" of a TCF, then, reflect the thinning edge of the original flake. Thus, overall, a TCF exhibits significantly more symmetry in comparison to most tool flakes, angular fragments and debitage. Future work will continue to study the fracture mechanics and conditions involved that result in the formation of TCFs.

Although calculating the curvature angle provided interesting results (that typical TCFs exhibit a curvature range of 170° to 177°, with 67% falling between 173°-176°), it was ultimately determined that, although the "eye" catches the curvilinear aspect, analysis to determine if TCFs are a distinct population are better served by capturing the notable symmetry

(EQ of SD width and SD thickness relative to TL and CH) of the piece. Our combination of multivariate and non-multivariate analyses indicate that although there is overlap between TCFs and other forms of lithics in the archaeological record, individual comparisons between fragment types indicate distinct differences. There are exceptions; for example, there appears to be significant differences in the adjusted curvature height of specimens from the FxJj 20 assemblage and that from the experimentally produced TCFs. In addition, although there are significant differences between assemblages of fragment types, there does appear to be substantial overlap in any one measurement. This suggests that multivariate methods may be a more appropriate means to distinguish TCFs from other types of fragments.

While many lithic artifacts are typed by morphology (e.g., flakes, blades, scrapers, axes, adzes, etc.), we recognize that this can be problematic. Therefore further research applying optical petrographic analysis of raw and heated materials (from the same parent materials as in this study) has been conducted, and is being prepared for publication. TCFs are included in that petrographic analysis.

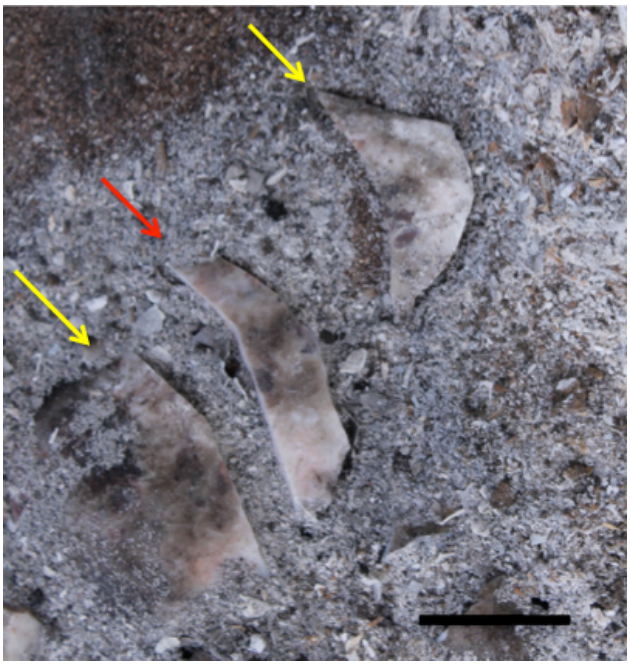

Figure 10. An *in situ* TCF being recovered from an experimental fire. Evident are the "break-points" of what was, originally, an entire flake. Although all three (visible) pieces (arrows) are technically produced by thermal curvilinear fracturing, only the *middle* piece specifically exhibits the characteristics of a typical TCF as we are describing herein. Scale = 2cm.

2.4.2 Review of archaeological angular fragment collections, and why so few TCFs?

The FxJj 20 site complex produced over 5000 stone artifacts during excavation in the 1970s (Harris 1978, 1997). Initial excavations suggested that this site presented possible evidence of human controlled fires (Clark and Harris 1985). Numerous artifacts in these initial excavations were identified as angular fragments. Here we review several specimens from this collection that exhibit patterns similar to experimental TCFs. Once the TCF morphology was identified, it was realized that the "eye" could recognize the peculiar symmetry—and a review of extant collections was warranted (Figure 11).

FxJj20 artifacts that conform to the morphological distinction of a TCF are relatively few (addressed below) considering the high frequency of fragments recovered from the site complex

(only 14 TCFs out of over 1500 fragments). However, in light of the *other* lines of evidence amassed at the FxJj20 sites—including rubified circular sediment features and spatial considerations of artifacts and activity areas corroborating these as hearths, thermoremanence, pyrolized phytoliths, and burned bone (Bellomo 1994; Cutts et al. 2016; Harris 1997; Hlubik et al. 2017, and *in press*; Ludwig 2000)—the TCF evidence bolsters the view that *Homo erectus* at ca. 1.5-1.6Ma may have begun to incorporate fire into their behavioral repertoire.

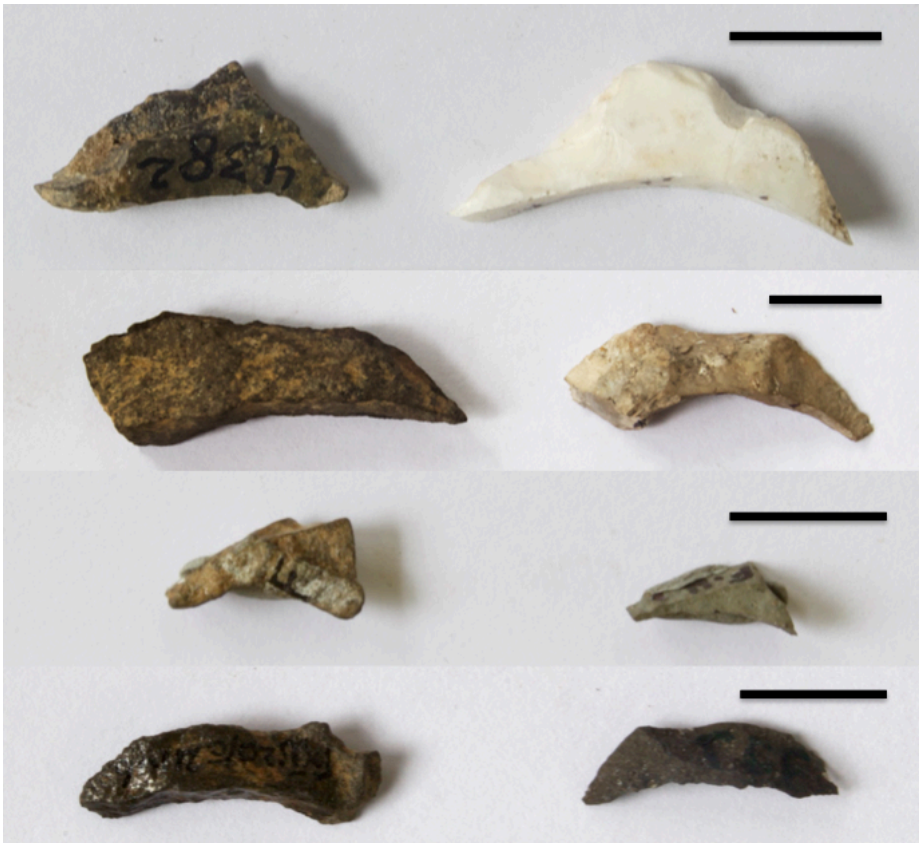

Figure 11. Four potential TCFs from the FxJj20-Main and –East "angular fragment" collection (on left), paired against experimental TCFs. The archaeological samples are statistically indistinct to the experimental TCFs. Scale bars all represent 1cm.

Not every fired flake will produce TCFs, yet in most experimental fires that included flaked stone, TCFs were produced. As flaked stone artifacts are exposed to fire, they may

initially fracture creating these characteristic TCF forms. Extensive exposure to fire, beyond the time it takes to form TCFs, may result in further crumbling of the rocks. From the flakes, bifaces and cores that were burned in our experiments, 192 TCFs were created. The TCFs varied in size, height, and width depending on the size and shape of the original flake.

There are likely several reasons why TCFs occur in fewer numbers compared to debitage. Our experiments intentionally burned rocks to ascertain how they change, and this certainly produced a significant number of (statistically distinguishable) curvilinear fragments. There is currently little reason to expect that early hominins were intentionally putting useful flakes and cores into fires. Archaeological and ethnographic evidence does record, however, that human tool-makers, including knappers, will sit near fires—for comfort, light, protection, etc. (Alperson-Afil and Goren-Inbar 2010; Binford 1983; Gowlett et al. 2005). Experimental knapping clearly indicates that, although much debris falls near the maker, it is not uncommon for the force of impact to distribute debitage. Perhaps some of these flakes made it into a fire hot enough to produce a TCF.

Many of the materials selected by humans to make stone tools have high silica content. In addition these materials (e.g., chalcedony) tend to be homogenous and fine-grained, with relatively few inclusions. Chalcedonies, which have water bound in the matrix as silanole, will dehydrate and often shatter or crumble when heated dramatically. In our experiments, it seems that a TCF is one form in a series of degradational states leading to eventual friability. Basalt, being a volcanic material, may be more resistant to heating, and indeed it tends to produce TCFs at lower rates than other materials. As basalt accounts for up to 90% of lithic assemblages in the Koobi Fora Formation (Toth 1987; Braun et al. 2008), few TCFs might be expected.

The relatively few potential archaeological TCFs in this study may be a product of the specific conditions required to create TCFs—namely that they occur most often when tool flakes are rapidly exposed to hot fires. In other words, scenarios where a flake is situated on a land surface that subsequently has a fire move across it, the slow increase in temperature may not result in the fracture that produces characteristic TCFs (discussed further below). However, if hominins are knapping near a fire and a flake happens to land on an already hot fire, then the rapid change in temperature may cause the types of fracture that results in the production of TCFs.

2.4.3 The issue of natural exfoliations

TCFs are likewise distinct from naturally-weathered exfoliated pieces. Any superficial similarity is due to the curvature of the weathered exfoliation. The highly symmetrical and evenness quotient of width-to-thickness along the piece, in relationship to the length and curve height is what most distinguishes TCFs from other fractured rocks.

2.4.4 The issue of natural landscape fires and lithic scatters

The USDA Forest Service landscape fires in this study provided some initial insight into whether wildfire temperature and duration at ground level can produce TCFs, and this is critical in the determination of whether TCFs may be an indicator of human-controlled fires. The lack of TCFs may be due to the ground itself acting to keep the flakes "cooler" while the fire-line passes over (Hartford and Frandsen 1992). Fuels determine fire type (flaming versus smoldering combustion) and fire residence time. The type and duration of combustion determines soil heating. Fast-moving landscape fires can be quite hot (some exceeding 1000°C). It is easy to assume that they could cause stone tools to behave in the same manner as a campfire. Fine fuels, (grasses, and shrubs) typical of African savannas have a very short (fire) residence time and

would likely result in relatively little heat on the soil surface. As a result, stone artifacts that were subjected to the effects of a wild fire in the past are unlikely to exhibit the same features seen during exposure to campfires (Shea et al. 1996).

Natural fires move rather rapidly, and do not bake sediments very deeply (Clements 2010). Although flame temperatures often reach 800°C in surface fires, the residence time can be quite short (<30 minutes). Furthermore, the highest temperatures in landscape fires are *not at ground level*. In many instances the ground-surface temperatures of landscape fires may not even exceed 250-300°C. One study conducted at Mpala Ranch, Laikipia Plateau, Kenya in mixed woodland/grassland reported ground temperatures from eighteen experimental burns did not exceed 190°C (Kimuyu et al. 2014). As well, the residence time of even the highest ground-level temperatures in a moving fire-line may be measured in minutes in some surface fires. Variation in the kinds of fuels within a savanna (e.g., treefall) might provide a longer exposure to high temperatures and it is this variation in how fuels burn that has led to more sophisticated measures of fire behavior being employed rather than temperature alone. Measuring heat energy rather than temperature is a much more salient predictor of fire effects (Kremens et al. 2010). Temperature is best applied as an index of hotness over relatively short time frames. However, heat defined in terms of energy flux, density or total energy can be used to predict the work done by the fire. Heat energy is likely a better predictor of the likelihood of TCF production than temperature. It is noteworthy that a stationary, multiple-hour (even days or more), managed (nursed, fed) ground-level campfire releases considerably more energy at one location (and onto objects at that location) than a quick-moving fire-line. To reiterate, although the temperatures reached by landscape fires and campfires may be the same, the heat energy in one location produced by campfires (because of their consistent fuel and long duration) can be much greater.

The long duration of elevated temperatures that occur in campfires produces the significant heating of the soil and rock fragments that can distinguish these different types of combustion (Busse et al. 2013).

2.5 Conclusions

Numerous features have previously been used to identify the presence of burning on stones. Many of these features are qualitative and subjective, such as color and texture. There exists an equifinality in the color of stones and various processes that can influence these colors that reduces the suitability of these features as indicators of human control of fire. While color changes or fracture patterns associated with FCR may not always be unequivocal as to heat-history, the TCF morphology can indicate the need for further study (i.e., petrographic analysis, thermoluminescence, etc.) to determine heat-history.

The control of fire is possibly one of the most significant technological advances in the history of our species (Wrangham 2017). Fire-cracked rock is a large class of artifact, widely found in archaeological sites around the world. What is surprising is that FCR has been so "understudied", relative to so many other artifact classes (e.g., lithic production, tool use, bone cut- or tool-marks, ceramics, architecture, trade, etc.). It is clear that FCR has much to offer to archaeological inquiry, and the realization that specific FCR—thermal curved-fragments—can be used to clearly infer *human-controlled fire* should inspire researchers to broaden our hypotheses and experiments to tease more useful data from this abundant artifact class. Exposure of artifacts to the long duration high temperature fires that characterize campfires are likely to produce other characteristic patterns that could be identified using a variety of techniques (e.g. petrography, 3D modeling and geometric morphometrics).

Thermal curved fragments are a distinct, quantifiable, class of artifact that indicate a *confluence of human knapped stone and hot, long, high-energy fires at ground level* (e.g., hearths and campfires). They can be statistically distinguished from unheated knapped debitage, as well as naturally exfoliated pieces. Natural landscape fires do not, typically, exhibit energy-release conditions at ground-level that would cause surface lithics to yield a TCF. Unmodified cobbles or natural stony materials exposed to fire do not have the requisite characteristics—platform, bulb of percussion, tapering terminal edge—to impose the TCF form on the heat induced fracture. Applied in concert with the other novel techniques recently advanced in the study of human-fire, TCFs can strengthen our inferences of this ancient behavior.

While the presence of a TCF-type artifact on a site does not "prove" that humans were using fire at that locality, we suggest that this readily recognizable morphology can be used as an indicator of the potentiality of human-controlled fire on a site. A TCF might suggest to a researcher that other lines of fire-evidence should be pursued at that location, which could be particularly useful on open-air and ephemeral sites. That this artifact is lithic is a boon, in that lithic materials preserve so well in the archaeological record.

The identification of TCFs could provide much-needed assistance in the search for understanding hominin control of fire. Once the type is recognized, they are visibly distinguishable from debitage and other lithic debris. Although this study used a comparison to archaeological materials from ESA sites in Kenya, the TCF morphology should be applicable and generalizable to any site, geographic location or time period wherein humans produced knapped stone tools and are suspected of controlling fire. Indeed, application of the TCF model will assist on archaeological sites of any age, but should be especially helpful on Early Stone Age sites that may not preserve or present other, conventional, evidence typically used to infer

anthropogenic fire. It is hoped that researchers will utilize the TCF model to revisit collections, in particular ESA sites reported with potential evidence of hominin-controlled fire.

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Chapter 3.

MINERALOGICAL AND TEXTURAL ALTERATION OF HEATED TOOL-STONES: ADVANCES IN UNDERSTANDING FIRE-CRACKED ROCK[2]

[2] Cutts, R.B., E. Garrison and M. Pistone. Submitted to *Archeometry*, 5/11/21.

Abstract

Fire-cracked rock (FCR) is a common artifact in archaeological assemblages. While some studies have explored FCR, a comprehensive treatment is unavailable. We report here an analysis of rocks including andesites, cherts, and ignimbrites (commonly used as knapped stone tools), that were exposed to a variety of controlled temperatures and time durations roughly correlating with varying fire types (e.g., fast-moving landscape fires vs. concentrated campfires). Samples were thin sectioned and examined petrographically to ascertain if mineralogical and textural changes in the rock can be linked to the experimental temperatures and times. Results suggest (1) few changes occur below certain temperature thresholds; (2) changes (e.g., oxidation, friability) that occur above these temperature thresholds (e.g., ~400-500°C for chalcedonic materials, and >800°C for andesites) are somewhat consistent within rock type; (3) some widely held (usually naked-eye) perceptions of FCR may not be commensurate with actual fire-history of the material; and (4) petrography may assist in clarifying heat-history of stone artifacts exposed to fire. The goal is to evaluate FCR's potential to inform on the important question of distinguishing anthropogenic versus natural landscape fire in archaeological assemblages. Results indicate that petrography has potential in FCR studies in clarifying the nature of fire temperatures/durations in prehistoric archaeological sites.

3.1. Introduction and background to the study

3.1.1 *Optical petrography analysis of heated stone*

Stone artifacts, especially knapped tools, are among the most prominent elements in the archaeological record, and our goal is to establish baseline data on a variety of rocks—and how fire affects them—widely used in both space and time. Additionally, in that both temperature and duration—actually a measure of total energy expended—may vary considerably among different

fire "types" (e.g., wildfire vs. campfire), we attempt to document changes in rock (commonly used as tool-stone) across a series of temperatures and durations that may be significant with regards to approximating these ranges. Unheated and heated samples are described and compared macroscopically, and subsequently thin-sectioned and examined using an optical petrographic microscope. See Table 4 for a list of materials in this study.

Table 4. Materials used in this study

Material	**"Archaeological" Description**	**Source Location**	**Munsell color** (unheated)	**Munsell color** (heated 500°)
Basalt (andesite)	Grey/black; coarse grained with small crystal inclusions	Areas 11, 5 and 131, Ileret and Karari, Kenya	GLEY1 2.5/N	White to 2.5YR 4/6
Chalcedony: translucent brown	"Jasper"/chert type; caramel colored; fine-grained homogenous	Il-Eriet Laga, Area 11, Ileret, Kenya	7.5YR 4/6	10R 8/1
Chalcedony: grey	Blended translucent and opaque grey; fine-grained, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	GLEY2 8/10B	10YR 8/1
Chalcedony: mottled pink/white/brown	"Chert" type; mottled colors pink, white, caramel, dk brown, beige, dk grey; fine-grain, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	10R 8/2; 2.5YR 2.5/1; 5YR 5/6; 5YR 3/4; white	2.5YR 7/3, 7/1
Chalcedony: mottled purple/brown/grey	"Chert" type; lightly mottled purple, purple-brown, dk grey; fine-grained, glassy	Area 5, Ileret, Kenya	10R 2.5/1	7.5YR 6/2
Chalcedony: pink/beige	"Chert" type; pinkish-beige with black	Il-Eriet Laga, Area 11, Ileret, Kenya	7.5YR 7/3	White (opaque)

	speckling and spidery line; fine-grained			
Chalcedony: translucent blue	Pale blue translucent; very fine-grained homogenous, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	GLEY2 8/10B	White to GLEY2 8/10B
Chalcedony: translucent grey	Translucent grey w/ minute black speckles; fine-grained, homogenous	Area 5, Ileret, Kenya	GLEY2 7/5PB	white
Chalcedony: translucent grey/green	Mottled grey-green-yellow; homogenous, extremely fine-grained, glassy	Il-Eriet Laga, Area 11, Ileret, Kenya	2.5Y 8/1, 8/2, 7/1	2.5YR 4/8
Chalcedony: yellow	"Chert" type yellow with quartzite inclusions; medium grained	Il-Eriet Laga, Area 11, Ileret, Kenya	10YR 4/4; 10YR 8/1	10R 8/3
Chalcedony: black/brown	"Chert" type 'tiger eye' appearance; swirled bands of caramel in black, w/ white flecks; coarse grained	Il-Eriet Laga, Area 11, Ileret, Kenya	10YR 5/6; GLEY 2.5/N; 10R 8/1	Black GLEY 2 2.5/N
Chalcedony: brown	"Chert" type; brown caramel; fine-grained, homogenous, glassy	Flint River, Albany, Georgia, USA	5YR 5/6	5RP 6/2; 10YR 8/6
Chalcedony: grey	"Novaculite" type; gray banding; fine-grained, homogenous, glassy	Arkansas, USA	5Y 7/2	5Y 6/2; 5BG 7/2
Ignimbrite: pink	Red/pink; coarse grained with crystal fragments	Area 11, Ileret, Kenya	10R 6/6	GLEY1 5/10Y
Ignimbrite: green	Green/gray; coarse grained	Areas 11, 131, Ileret and Karari,	GLEY1 6/10GY	GLEY 1 2.5N

	with crystal inclusions	Kenya		
Quartzite	White; coarse grained	Area 11, Ileret, Kenya	White; very light gray 8.5N	10R 7/1

3.1.2 Archaeology of fire

Control of fire is widely perceived as one of humanity's most important technological achievements. The archaeology of fire, alternatively, may be described as "immature" (Gowlett and Wrangham 2013). The reasons for this disconnect are reasonably straightforward.

First, the archaeological record is incomplete (Binford 1983). Taphonomic and preservation pressures bias against archaeological features and evidence that otherwise are construed as *clear* indications of human-controlled fire (Gowlett 2016). For example, a multi-layered hearth exhibiting several layers of ash or charcoal, tightly circumscribed and in direct association with derived artifacts would generally be accepted for evidence of human fire (Berna and Goldberg 2007; Goldberg et al. 2012; Karkanas et al. 2007; Shahack-Gross et al. 2014; Shimelmitz et al. 2014). While such features may be more common in late Middle Stone Age (MSA) or later, they are far less likely to be preserved from earlier time periods. When they are present, mitigating circumstances (e.g., a cave setting) are often implicated in their preservation. Open-air sites are not likely to be as well-preserved (Berna et al. 2012; Gowlett 2016).

Moreover, remains of fire on archaeological sites are often equivocal. Many natural processes can yield similar results, and such ambiguity may confuse interpretations of human-controlled fire. Examples may include natural wildfires causing "potlidding" on stony outcrops, landscape fires sweeping activity areas and modifying knapping debitage, or the unfortunate reality that "reddened, blackened or whitened" rock does not, inherently, indicate exposure to a fire. Indeed, the mere presence of charcoal, ash or other fire remains on an archaeological site do

not, in actuality, automatically suggest human control; natural fires can leave these traces as easily as a managed campfire, and the movement and redeposition of these remains may obfuscate their origin (Aldeias 2017; Gowlett et al. 2017).

These inherent challenges to archaeological investigation of human controlled fire may have inadvertently discouraged rigorous development of hypotheses in research of (early) human control of fire. While studies on topics such as stone tool technology, ceramics, diet, and modifications on butchered remains—among many other important subjects—have yielded insightful and informative (if not always unequivocal) treatment, the archaeology of fire has not progressed as rapidly (Goldberg and Aldeias 2016; Gowlett and Wrangham 2013; Roebroeks and Villa 2011).

Even with these challenges, notable research on the archaeology of fire supports the idea that avenues are available to advance this field. Focusing on recovery techniques, with a goal of 100% recovery with spatial data intact, may help address the anthropogenic origin of fire remains (Alperson-Afil 2012; Hlubik et al. 2017, 2019; Goren-Inbar et al. 2004). Pursuing advancing geological techniques in application to archaeological inquiry has also proven valuable; for example, working with petrography to analyze ceramics has informed on firing temperatures, construction techniques and materials sourcing, while micromorphological sediments and pyrolized phytolith samples can infer use patterns in and around hearths as well as fuel-choices (Albert et al. 2003; Albert, Berna and Goldberg 2012; Aldeias et al. 2016; Berna et al. 2007; Courty et al. 2012; Elbaum et al. 2003; Rasmussen et al. 2012; Schmidt et al. 2012; Stoltman 2001; Werts and Jahren 2007).

In the current study, we build upon geoarchaeological and microscopic advances to test hypotheses regarding whether (H_n) no significant changes can be mapped to temperature and

duration in fire-affected stone, or (H_1) noteworthy changes are traceable in fire-affected stone, and may infer distinction between anthropogenic and natural fires. We test whether insights regarding the nature of human-fire relations may be inferred from distinct modifications of fire-altered lithics of the type recovered from archaeological sites.

3.1.3 Ambiguity in fire-cracked rock

Fire-cracked rock (FCR) is a common artifact in archaeological sites, yet no comprehensive, standardized, treatment of the type exists. Early studies determined that, unlike knapped stone tools, FCR may not clearly show platform, bulb of percussion, ripple marks and other indicators of Hertzian mechanical fracture (Cotterell and Kamminga 1987; Purdy 1975; Purdy and Brooks 1971). Further studies introduced new terms for the particular way fire can break rock; FCR may express as angular shapes variably described as jagged, curvilinear, contorted, irregular, spalled, pot-lidded, crenulated, crenated and so on (Jackson 1998; Latas 1992; McParland 1997; Taggart 1981; Thoms 1986, 2008, 2009). Additionally, fire-exposed rock may show changes from the raw, original, color; usually this color change is expressed as a reddening (oxidation) of iron oxides (Purdy and Brooks 1971; Sorenson and Scherjon 2018). Unfortunately, in many of these examples, ambiguity exists in that natural processes can obfuscate clear association of anthropogenic origin. However, a recent study described a macroscopically identifiable angular fragment, termed a *thermal curved-fragment* (TCF), produced from knapped stone being exposed to high heat over long duration (Cutts et al. 2019).

3.1.4 Variable effects of fire

While fire is straightforward in definition—a chemical combustion process requiring heat, fuel, oxygen and unrestrained chain reactions—the effects of fire can be variable. For example, whether an object being heated is subsurface, at the surface, or elevated will affect the

work of heat energy on that material. Duration of exposure—e.g., fast moving landscape fires compared to maintained, concentrated, campfires—will also yield variable effects.

For archaeologists, the issue of landscape fires (often lightning ignition) versus human fires (a variety of ignition, including opportunistic "borrowing" from landscape fire) is a perennially challenging topic. Wildfires may obfuscate clear association of human activity (with fire) on archaeological sites (Barbetti et al. 1980; Bellomo 1993; Buenger 2003; Goldberg et al. 2017; Gowlett et al. 1981; Klein 2009; Oakley 1954). A few studies have attempted to evaluate techniques that may discriminate between the effects of wildfires and human fires (Bellomo 1993, 1994; Cutts et al. 2019; Gowlett et al. 2017; Toffolo and Boaretto 2014). Such effects may present in artifacts, features, soils and sediments, magnetic susceptibility, and microremains. Indeed, most all aspects of an archaeological site may be vulnerable to the modifying effects of landscape fires. This has led some to conclude it may be impossible to determine between effects of landscape and human fire; the sentiment is represented by statements such as "The difficulty of separating natural from human burning at ancient open-air sites and the rarity of equally ancient caves means that reconstructing the history of human fire use may always depend more on speculation than on archaeological discovery" (Klein 2009:414).

There are ways to address this situation. Archaeological discovery alone is not capable of reconstructing the human history of fire. A collaborative effort among geologists, geographers, fire ecologists, primatologists, and archaeologists—among others—is what may ultimately provide insights into this history. An interdisciplinary approach is required. For example, our collaboration with USDA Fire Ecologists has led us away from primarily using temperature to distinguish between anthropogenic and wild fires, yielding a more nuanced perspective on the

nature of fires (contra Bellomo 1994; e.g. Clements 2010; Cutts et al. 2019; Gowlett et al. 2017; Hartford and Frandsen 1992; Shea et al. 1996).

Experimental studies by archaeologists interested in the effects of fire on sediments and soils under campfires indicate that modifications are limited—heat rises and may not penetrate deeply—and quantifiable (Aldeias et al. 2016; Gowlett et al. 2017). These results are corroborated by ecological studies of fires—some of which are much larger, yet more transient, than typical human campfires—in a variety of conditions (Busse et al. 2013; Clement 2010; Hartford and Frandsen 1992; Kimuyu et al. 2014). Gowlett and Wrangham (2013) suggest "[H]uman fire breaking free will resemble a wildfire, but a wildfire 'burning small' will not exactly mimic hearths." Single locality long-duration high-intensity fires (i.e., campfires) release considerably more energy on that local (ground level) environment and materials thereon (e.g., rocks used as fire 'furniture' or stone knapping debitage) compared to the majority of fast-moving landscape fires of similar temperatures.

In this paper, we present findings of a study investigating effects of fire on stony materials commonly used in the production of lithic tools by humans and their hominin relatives. This research sought to ascertain and map changes in rocks at different temperatures and durations that may help differentiate lithics exposed to natural landscape versus anthropogenic fires.

3.2. Methods

Material for these studies was procured from North America and East Africa. Basalt, novaculite and chalcedony (Flint River Chert) were selected from areas in the USA. Andesite, ignimbrite and chalcedony were collected from the Koobi Fora, Sibilioi National Park region of Kenya (Table 4).

The stone was knapped using appropriate Early Stone Age technology (hard hammer percussion, free-hand, no copper billets or modern tools; Toth 1987). Five flake samples of each material were selected. A raw (unheated, natural) piece was retained as a control and comparative sample against which heated samples could be analyzed. The other four pieces of each rock type were subsequently heated in a Lindberg 1700 Watt Box Furnace. Temperatures were recorded using a Shenzhen Handsome Technology IR Thermometer HT6885 (range 50-1050°C, with basic accuracy of +/- 2°C). A first phase of experiments heated samples—each sample to only one temperature and duration—to 250°C, 500°C, 750°C and 1000°C respectively. Once peak temperature was reached, it was held for 3 hours. At the end of this dwell time, the furnace was turned off and the sample retrieved after the furnace was fully equilibrated at room temperature. A second round of experiments repeated the sequence for select materials, with the following modifications: samples were heated to 1000°C for 5 mins, 30 mins, 1 hour, 5 hours and 24 hours (again, one sample for each of these conditions).

Samples were labeled according to type and exposure. After recording visually recognizable (macroscopic) modifications (color, luster, texture), samples were thin sectioned by Quality Thin Sections (Tucson, Arizona).

Thin sections were examined using an optical petrographic microscope. Photomicrographs were taken using an Apple iPhone7®. Thin section description focused on identification (i.e., corroborating field identification of materials) and clarifying modifications as affected by heating at the distinct temperatures (and durations) mentioned above. Selected thin sections were analyzed using Scanning Electron Microscopy (SEM) – Energy-Dispersive Spectroscopy (EDS) at the Georgia Electron Microscopy Center of UGA and X-Ray Diffraction (XRD) in the Department of Geology at UGA. Selected samples were analyzed with the JEOL

8600 electron microprobe using a 15KV accelerating voltage and 15nA beam current at the Department of Geology at UGA. Mineral grains were qualitatively identified using a Bruker 5010 Silicon Drift Detector (SDD) energy dispersive x-ray (EDS) detector controlled by a Bruker Quantax energy dispersive analysis system. Quantitative analyses were performed with wavelength dispersive spectrometer automated with Advanced Microbeam, Inc. electronics and Probe for EPMA software, using 10 second counting time, and natural and synthetic mineral standards. EPMA and SEM-EDS analyses were conducted using a secondary standard (glass F0 from Pistone et al., 2016) used to verify the reliability of the chemical measurements. Analyses were calculated using the Phi-Rho-Z matric correction model (Armstrong 1988). Backscattered electron images (BSE) were acquired using imaging software of the Quantax analysis system. Selected thin section samples were analyzed using the XRD system Bruker D8-Advance with data analysis computers supported by NEWMOD, CrystalDiffract, Wildfire, CrystalMaker and the ICDD PDF-2 data base.

3.3. Results

A summary of results is provided in Table 5. Here, results will focus on effects such as color and textural changes that help archaeological interpretations regarding the question of anthropic versus natural landscape fires. It is worth noting that in addition to the following results, a few of the stone material samples in this study – including chalcedony, ignimbrite and andesite – were *incorrectly* identified in the field. For example, what was identified in the field as “basalt” (Karari and Ileret samples D and L) were subsequently determined (via SEM analysis) to be andesite; another material identified as “white ignimbrite” in the field was later determined to be chalcedony (via thin section petrographic analysis). This will be addressed further in the Discussion section.

3.3.1 Color and textural changes at temperature

Highly siliceous materials (e.g. chalcedonic types) exhibit textural changes typically beginning at ~500°C, becoming increasingly weak and friable. This effect seems to be consistent in all chalcedonic materials. Additionally, ignimbrites are also dramatically weakened at and above 500°C. Andesite does not exhibit this tendency towards friability, remaining durable.

Color changes include consistent opaqueness in heated chalcedonic materials that were translucent when raw. Chalcedonies exhibit highly variable color upon heating, including red, purple, yellow, pink, white and brown. Even within one chalcedonic material, however, there were not necessarily consistent changes. For example, unheated East African Chert (samples F1-F5) exhibiting pinkish-beige with small black inclusions became dark grey at 250°C, grey-brown at 500°C, white and pink at 750°C and solid white at 1000°C. Similarly, East African Chalcedony (samples E1-E5)— unheated being translucent amber banded by white—showed no change at 250°C, became pink and white at 500°C, grey-white with red speckling at 750°C and chalky-white with black banding inclusions at 1000°C.

Green ignimbrite (grey-green unheated; samples B1-B5) shifted to brown at 500°C, red at 750°C and dark red-brown at 1000°C. Red ignimbrite (red-pink unheated; samples J1-J5), simply became a deeper red at 750°C and 1000°C. Andesite (black unheated; samples D1-D5, L1-L5, R1-R5, S1-S5) showed no discernable color change at any temperature or duration.

Table 5. Summary of results

General Type	**Notes** (Appendix A Samples)	**Macroscopic**	**Microscopic** (thin section)
Ignimbrite	B1-B5; J1-J5	250°C - No visible color or textural change; 500°C	No significant color or structure change at 250°C or 500°C;

		- oxidation/darkening red, friable; 750°C and above - oxidized to deep red/ brown, flat luster, friable/ crumbling	flattened pumice clasts appear reduced at 750°C, becoming pronounced at higher temperatures, groundmass oxidized dark red-brown; micro-cracking and small voids at 1000°C
Chalcedony	E1-E5; F1-F5; G1-G5	250°C - No significant color or textural change, occasional loss of translucence; 500°C and above - opaque, pink, white, red, brown, grey, black, purple, flat luster, friable, cracking, chalky	No significant color or textural change at 250°C; 500°C – some microfracturing of quartz, disorganization of feathery quartz intergrowth, oxidation reddening; 750°C – fibrous habit quartz disintegrating and discolored to beige, brown and red, microfracturing, increasing homogenous salt-and-pepper appearance; 1000°C – fibrous quartz homogenized to salt-and-pepper appearance, oxidized brown, red, grey, microfracturing
Andesite	D1-D5; L1-L5; R1-R5; S1-S5; U1, U2	250°C to 1000°C – no color or textural change	250°C – 500°C – no significant change; 750°C – some disorganization of phenocrysts, unclear process; 1000°C for 3+ hours – significant voids present, smooth-edged, circular to ovoid; No significant change in natural vesicular basalt (heated), vesicles are irregular-edged, jagged, ovoid to linear, edges often include phencrysts of pyroxene and olivine

3.3.2 Petrographic descriptions of changes at temperature

Thin section descriptions of samples reported here are available in Supplementary Materials (Appendix A). We present here selected results highlighting significant findings.

3.3.2.1 Ignimbrite – green and red (Appendix A; B1-B5, J1-J5)

Unheated ignimbrite is flow banded eutaxitic lapilli tuff, with a groundmass of welded glass shard. Interspersed are flattened pumice clasts and phenocrysts of biotite, quartz and

feldspar. Samples heated to 250°C show no significant change. However, above 500°C the flattened pumice clasts begin to disrupt, and this effect is pronounced at 1000°C (Figure 12). While phenocrysts persist, their overall size often reduces, and flow banding of the groundmass effect is less distinct, and pumice clasts appear reduced. Evidence of oxidation (reddening) is present.

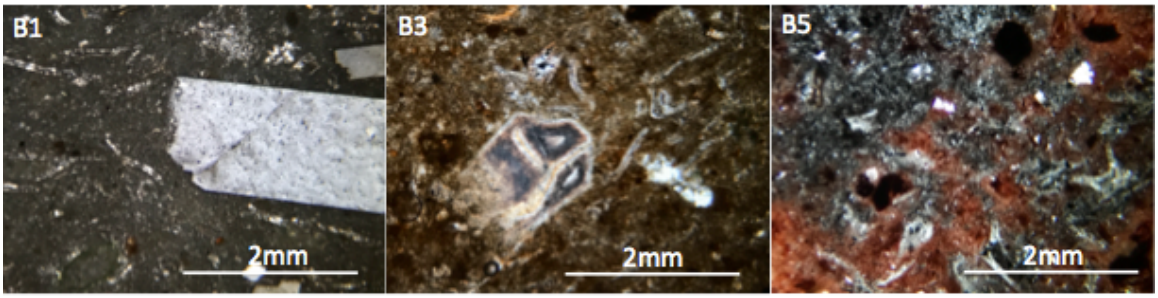

Figure 12. East African Green Ignimbrite, in XPL. From left: samples B1 (unheated), B3 (500°C) and B5 (1000°C); heated for 3 hours. Some pumice clasts appear disrupted in B3 and greatly reduced/fragmented in B5. Oxidation (reddening) is also apparent at these higher temperatures.

3.3.2.2 Chalcedony (Appendix A; E1-E5, F1-F5, G1-G5)

Unheated chalcedony is composed by very fine-grained microcrystalline quartz with a black/white/grey "sandy" appearance – this is sometimes referred to as "salt and pepper" – intergrown with larger quartz veins of fibrous habit showing strong undulose extinction (Figure 13, left upper and lower images). Samples heated to 250°C show no significant modifications from unheated. Samples heated >500°C display larger fibrous crystals that disintegrate and turn a dull brown. Samples heated at 750°C and 1000°C exhibit a homogeneous "salt and pepper" appearance, interspersed with microfractures (Figure 2). Significant reduction of fibrous intergrowths is evident.

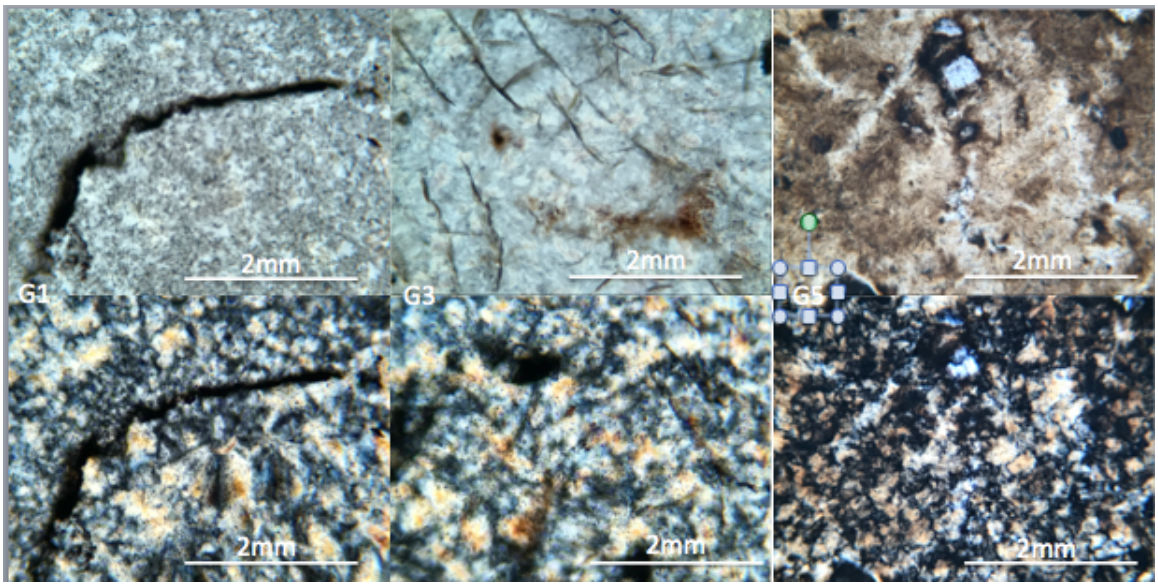

Figure 13. East African Chalcedony; top row in PPL, bottom row in XPL. From left, samples G1 (unheated), G3 (500°C) and G5 (1000°C), heated for 3 hours. Note the "salt and pepper" appearance of low-relief microcrystalline quartz in G1 (top left, PPL) and the feathery, fibrous, habit of same image in XPL (below left). Micro-cracking and oxidation begin to appear in G3 (500°C; middle top and bottom), as can be seen a reduction in fibrous habit of ingrown siliceous crystals (in XPL; middle, bottom). Oxidation and fragmentation of fibrous habit is evident in G5 (right). These tendencies are generally applicable across the chalcedony materials in this study.

3.3.2.3 Andesite (Appendix A; D1-D5, L1-L5, R1-R5, S1-S5, U1-U2)

Unheated andesite shows fine-grained groundmass of heavily flow banded plagioclase lathes exhibiting typical twinning, interspersed with porphyritic phenocrysts of biotite and pyroxene. No significant changes occur at 250°C and 500°C; however, beginning at 750°C and becoming pronounced at 1000°C, clearly visible voids appear (in sample D, East African Basaltic Andesite from Karari, Kenya; Figure 14). Higher temperature samples maintain an integrated groundmass of flow banded plagioclase lathes. The noticeable voids (in-filled now with the resin used to impregnate the thin section material) typically appear round, sub-rounded or ovoid and are distinctly smooth-edged. Careful macroscopic inspection of the sample (D5, 1000°C) can ascertain the vesiculation; it is noteworthy that the sample, *prior to thin sectioning*,

was not noticeably altered. Samples L1-L5 (East African Andesite from Ileret, Kenya) did not evidence this striking effect in this *first* phase of heating.

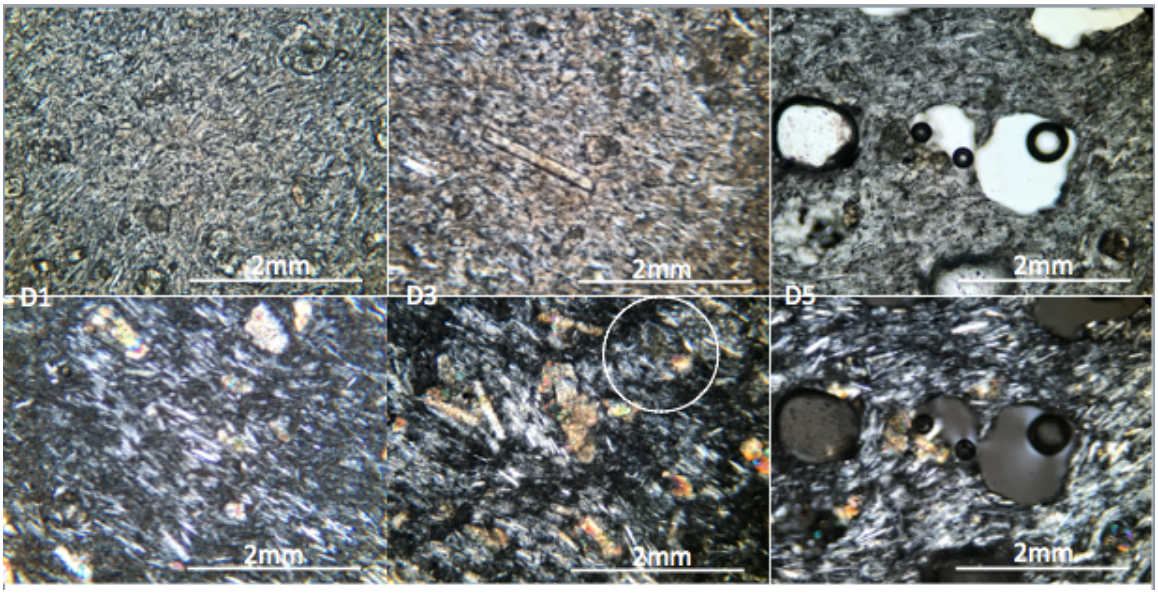

Figure 14. East African Andesite (Karari, Kenya); top row is PPL, bottom row is XPL. From left, samples D1 (unheated), D4 (750°C) and D5 (1000°C), heated for 3 hours. Although not visible in D5 sample prior to thin sectioning, once on the slide a textural change was slightly evident. Under magnification, D5 (1000°C) shows voids that may indicate lost material; subsequent XRD analysis of D1 and D5 indicate that pyroxenes may have reduced. A review of D4 slide suggests what may possibly be the initiation of this process (white circle in lower middle image).

The second round of andesite samples (same parent materials as samples D and L) that were heated to 1000°C for 5 minutes, 30 minutes, 1 hour, 5 hours and 24 hours (each sample for one duration) reinforced the results detailed above. Andesite at 1000°C for 1 hour or less does not exhibit voiding, whereas the samples heated for 5 hours or more do show this effect (Figure 15). Further, in this round of heating, sample S (from same parent as sample L, above) did exhibit the voiding at longer duration heating.

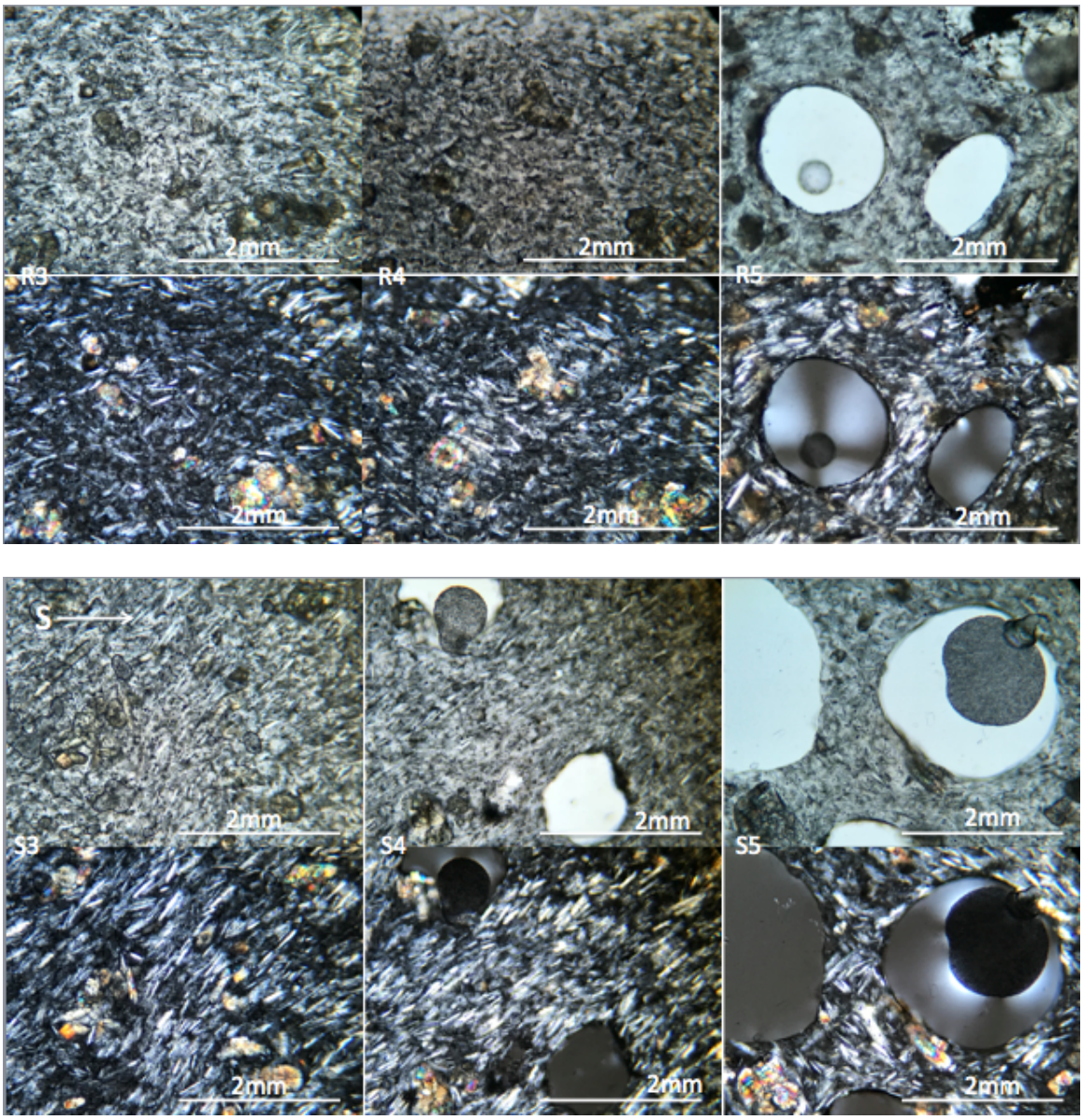

Figure 15. East African Andesite. Top row of each set is PPL, bottom row is XPL. Top set: R3, R4 and R5 (Karari, Kenya) at 1000°C for 1 hour, 5 hours and 24 hours respectively (left to right). Bottom set: S3, S4 and S5 (Ileret, Kenya) at 1000°C for 1 hour, 5 hours and 24 hours respectively (left to right). In these images and in Figure 3, note the round, ovoid or sub-ovoid shape of the voids, as well as the clean, "crisp" appearance along the edges of the voids.

Natural vesicular andesite, exhibiting vesicles that are visible macroscopically, was heated in the muffle-furnace at 1000°C for 3 hours. An unheated sample was reserved. Both unheated and heated vesicular andesites were compared against the effects of heating observed in

the Karari and Ileret andesites (both appearing macroscopically non-vesicular). Unheated vesicular andesite have a groundmass of plagioclase lathes interspersed with olivine and pyroxene, as well as the vesicles. Natural vesicular andesite voids appear distinct from the voids in heated andesite: whereas voids from heating are rounded or ovoid and smooth-edged, vesicular andesite voids can be rounded, elongated or linear with edges appearing jagged, irregular, usually transparent (thin edged) and often encasing small phenocrysts of olivine and pyroxene (Figure 16). The heated vesicular andesite did not show significant modifications.

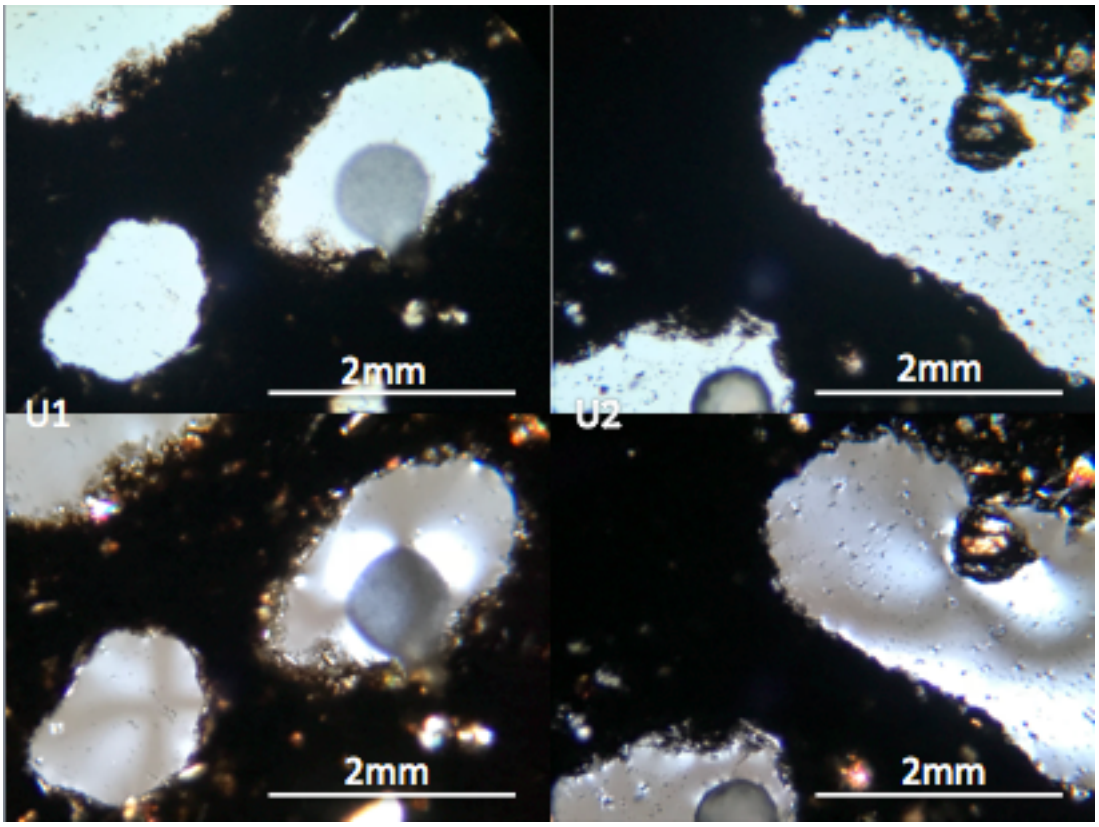

Figure 16. Vesicular andesite. Unheated on left, heated (1000°C, 3 hours) on right. Top row are in PPL, bottom row are in XPL. Note that the shapes and edge effect of the vesicles appear distinct from other heated non-vesicular andesite in this study: more elongated, and the transparent edges show phenocrysts of pyroxene, quartz and olivine.

3.3.3 XRD and SEM-EDS analysis

In order to evaluate if mineralogical changes were taking place due to heating, unheated and 1000°C andesite (samples D1 and D5, Karari Ridge, Kenya) was examined using both XRD and SEM-EDS. The XRD profiles suggest that at high temperatures there is lack of pyroxenes (Figure 17).

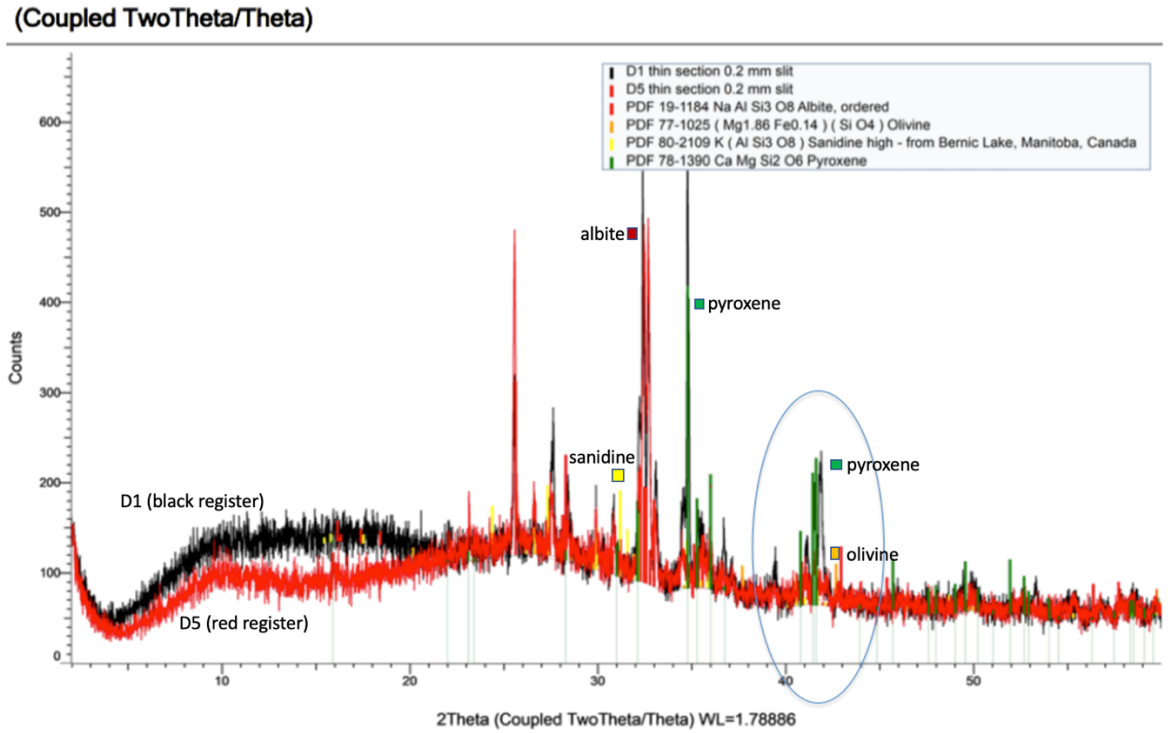

Figure 17. X-Ray Diffraction graph showing Karari andesite samples D1 (unheated, in black register) and D5 (1000°C, in red register). Note different indication of pyroxene at 42 on X-axis.

Considering that the XRD results are comprised of a small sample size, as well as the possibility of variation (of material) across a sample, the andesite samples D1, D5, L1 and L5 were analyzed via SEM-EDS. The residual glass composition in these materials at temperature above the glass transition temperature (T_g = 800°C, based on the model of Giordano et al. 2008, using the analyzed glass composition) becomes melt and, with water loss from the melt upon

heating above T_g, gets populated by isolated rounded and smooth-edged vesicles ranging from ~1mm to ~5mm in diameter, with an average of ~2mm.

Table 6. List of major element composition (in oxides, by wt.%) of andesite samples D1 (unheated, raw) and D5 (heated to 1000°C for 3 hours) of glass composition taken using EPMA and SEM-EDS analyses.

Sample	SiO_2	TiO_2	Al_2O_3	MgO	FeO	MnO	CaO	K_2O	Na_2O	TOTAL
D1 (EPMA)	75.7	0.7	11.7	0.1	0.7	0.0	0.5	5.1	2.2	96.7
D1 (EPMA)	74.5	0.8	11.3	0.0	0.8	0.0	0.2	5.7	2.2	95.5
D1 (SEM-EDS)	79.4	0.7	11.9	0.0	0.8	0.0	0.2	5.0	1.7	99.7
D1 (SEM-EDS)	78.9	0.8	12.2	0.0	0.8	0.0	0.3	5.1	1.8	99.9
D1 (SEM-EDS)	72.7	0.8	12.7	2.8	3.7	0.1	0.6	4.1	2.2	99.7
D1 (SEM-EDS)	79.8	1.0	11.4	0.0	0.9	0.1	0.3	4.8	1.6	100
D1 (SEM-EDS)	78.0	1.0	12.7	0.0	0.9	0.0	0.3	5.0	1.9	99.8
D1 (SEM-EDS)	78.5	0.7	12.5	0.0	0.8	0.0	0.2	5.2	1.9	99.8
D1 (SEM-EDS)	78.9	0.8	12.1	0.0	0.8	0.0	0.2	5.2	1.8	99.8
D1 (SEM-EDS)	79.1	0.8	11.9	0.0	0.9	0.1	0.3	4.9	1.8	99.8
D1 (SEM-EDS)	78.9	0.8	12.0	0.0	0.8	0.0	0.2	5.1	1.9	99.7
D1 (SEM-EDS)	80.0	0.8	11.4	0.0	0.9	0.0	0.3	4.8	1.7	99.9
D5 (EPMA)	62.1	0.1	22.2	0.0	0.9	0.1	5.7	2.0	5.9	99.0
D5 (EPMA)	76.1	0.7	12.9	0.1	1.1	0.0	0.9	4.9	2.6	99.2
D5 (SEM-EDS)	79.7	0.7	11.8	0.1	0.9	0.0	0.5	4.2	1.9	99.8

D5 (SEM-EDS)	78.5	0.6	11.8	0.2	1.7	0.0	0.6	4.7	1.6	99.7
D5 (SEM-EDS)	79.8	0.8	11.6	0.0	0.8	0.1	0.5	4.5	1.7	99.8
D5 (SEM-EDS)	73.3	0.6	14.8	0.3	2.5	0.0	1.7	3.9	2.7	99.8
D5 (SEM-EDS)	80.5	0.7	10.7	0.2	1.6	0.0	0.6	3.9	1.7	99.9
D5 (SEM-EDS)	80.2	0.8	11.0	0.2	1.3	0.0	0.5	4.1	1.7	99.6
D5 (SEM-EDS)	78.8	0.7	11.7	0.2	1.7	0.0	0.6	4.4	1.8	99.9
D5 (SEM-EDS)	79.6	0.6	11.6	0.2	1.5	0.1	0.5	4.0	1.8	99.9
D5 (SEM-EDS)	78.6	0.7	11.7	0.1	1.7	0.0	0.6	4.5	1.7	99.6
D5 (SEM-EDS)	79.9	0.6	11.1	0.2	1.4	0.1	0.5	4.3	1.7	99.8

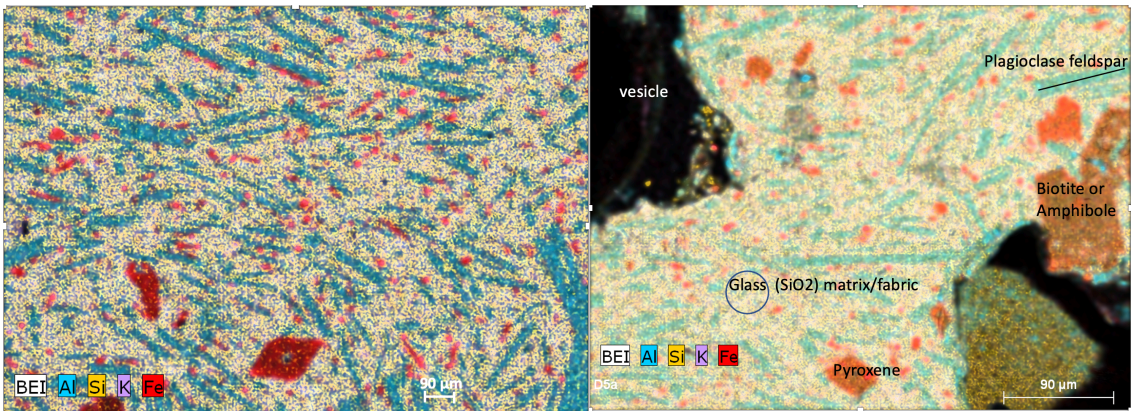

Figure 18. EPMA-based BSE images of sample D1 (unheated) composite image (left), and sample D5 (1000°C) composite image (right).

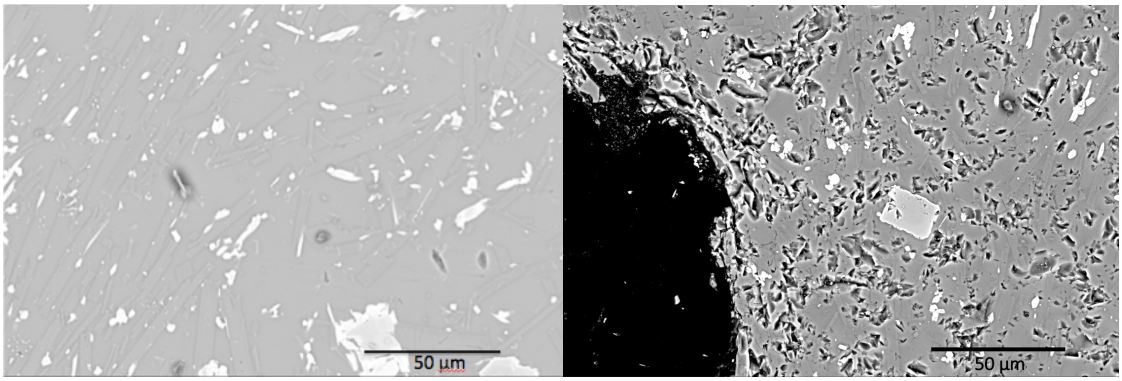

Figure 19. SEM-energy dispersive spectroscopy (EDS) of samples D1 (unheated, left) and D5 (1000°C, right).

3.4. Discussion

3.4.1 Color changes in heated tool stone

Previous studies (Jackson 1998; Purdy and Brooks 1971) have noted color changes in heated lithics (reddening, blackening, whitening, etc.). Our study both corroborates and refutes their works, revealing a more complicated situation. Heating lithic material can result in color changes—well beyond reddening or whitening. However, it is difficult to predict these color changes or use color to infer clear association with certain exposure temperatures/durations. In our samples, chalcedonic materials that were translucent while unheated became opaque between 250°C and 500°C (often white, but also pink or purple or brown). The same material may also change color several times as it moves through the temperature spectrum, confounding interpretation of temperature and duration (i.e., anthropogenic vs. natural fire). Another chalcedony may not show much color change through variable temperature, yet exhibit significant change microscopically as textural loss of fibrous fabric. As indicated by Sorenson and Scherjon (2018), luster or texture may be a more salient indicator of temperature and duration exposure, as opposed to color.

Although color is often used by field archaeologists to infer heated lithics, the current study suggests that—at least when considering siliceous materials such as chalcedony—texture and luster may be more important. Very consistently we found that chalcedonies exposed to 500°C and higher become friable. This is distinct from "heat-treated" material (i.e., heat-engineered annealing at low, controlled temperatures, for flakeability), which may exhibit a dull, waxy luster compared to unheated material (Brown et al. 2008). Color alone can be misleading: different researchers see colors variably; natural sunlight or indoor fluorescence highlights different tones. It is likely that, macroscopically, combining the use of a Chroma sensor with examination of luster and texture will yield more consistent and accurate assessment of the heat history of suspected thermally altered lithics.

Also indicated by the current study, some materials when heated show either no color change as observed in andesite samples or a color derived from material oxidation as observed in initially green ignimbrite turning red or red ignimbrite turning deeper red upon heating. Again, it is luster and texture (sometimes only visible microscopically) that may be more diagnostic in determining the heat history of lithic material in archaeological sites.

3.4.2 Petrography is useful to analyze FCR

This study reveals that in most lithic samples at least some changes due to heating were visible under petrographic examination. The results documented herein could be important to the question of differentiating between fast-moving landscape fires and stationary, maintained campfires, and the "energy work" accomplished on particular locations and materials. Additionally, combining optical petrography and SEM-EDS revised the identification (both "field" and initial laboratory) of the "basalt" in this study to andesite; and while to humans and earlier hominin ancestors the stone-tool functionality of basalt and andesite was likely

indistinguishable, it is appropriate that scientific inquiry work towards specificity. More broadly, it is clear that many field identifications of stone applied by archaeologists would be strengthened (and/or corrected) by laboratory analysis. This may be particularly important when field archaeologists make rapid (but unverified) determinations that an artifact is FCR; if the material in question is potentially misidentified, how can the heat-history of that artifact be similarly confirmed (outside of laboratory analysis)?

The andesite in this study – e.g., the phenomenon of "heat-induced vesicles" and what mechanism is causing it – produced inconclusive results. While XRD suggested loss of pyroxenes in the heated sample, it is not clear what process is leading to this reduction; it is possible that—over millions of years—some original pyroxene has weathered to hydrated secondary minerals (Wilson 2004) that may break down and lose water upon heating. Alternatively, it is also possible that this XRD analysis represents heterogeneous aspects of pyroxenes across the samples. The spot analysis via the EDS of the SEM displayed similar composition of the residual glass in both the heated and unheated samples. This suggested the possibility that no new vesicles were formed in the residual glass $>T_g$, and that the vesicles (i.e., in samples D5, L5, R4-5 and S4-5) are pre-existing in the original, parent material (i.e., formed during extrusion and emplacement of the original lava rock. After the SEM-EDS analysis, the original (unheated) and 1000°C materials were reviewed again using the optical petrographic microscope. Whereas the SEM-EDS indicated that no significant chemical or microstructural modifications occurred in the heated samples, we find it inconsistent with visible evidence under the optical petrographic microscope. It is unlikely a coincidence that these "smooth-edged and rounded voids", while *not* present in the unheated (raw) samples (D1, L1, and excepting the natural vesicular andesite, sample U1), are only exhibited in samples exposed to controlled

muffle-furnace heating at higher temperature (i.e., 1000°C) and longer duration (i.e., at least 3 hours or more, samples D5, R5, S4-5). Further, the presentation of "voids" in naturally occurring vesicular andesite is somewhat distinctive when compared to the "heat-induced voids" in our samples: natural vesicles are more "rough-edged", with translucent borders and less ovate, while the heated samples exhibit "voids" with very smooth edges, clean borders and are in general more ovate in shape (refer to Figs. 14, 15 and 16). Andesite can lose residual volatiles (such as water) and/or experience reorganization beginning at the glass transition phase temperature of around 800°C, and being pronounced at higher temperatures and longer durations. Studies have investigated this phenomenon and provided models aimed to estimate the T_g of volcanic rocks (Giordano, Nichols and Dingwell 2005; Giordano, Russell and Dingwell 2008). Careful examination of the unheated samples (D1, L1) – with the unaided eyed and microscope – does not indicate the presence of vesicles (i.e., formed during extrusion and emplacement of the original lava), and yet – while the IR thermometer recorded temperatures commensurate with T_g of these materials – this study shows that temperature exceeding 1000°C may be required to chemically or structurally modify the volcanic rock.

Therefore, while at this time we cannot state unequivocally what process yielded the voids in our heated basalt/andesite samples, we can share a few archaeologically-salient impressions. First, in most open-air campfire situations – regardless of time period (e.g., Early Stone Age, Middle Stone Age, Upper Stone Age) – the temperatures of anthropogenic fires are unlikely to rise to T_g of an andesite or to stay at that intensity for long enough for the energy-work of the fire to result in the same. Further, unlike natural vesicular andesite, voids in heated andesite are not immediately visible macroscopically; it is after thin sectioning that voids become recognizable, and only under microscopic examination that their nature becomes clear.

Additionally, even if these tiny voids were noticed with the naked eye, they would not appear different from naturally occurring vesicles. Examining vesicular andesite under thin section reveals that the nature of the vesicles, both in overall dimension and in vesicle-edge presentation is distinct from heated andesite voids. However, in that ~90% of knapped tool stone from Early Stone Age sites in Africa is andesite, any inquiry as to the early anthropogenic (hominin) control of fire may well be augmented by a review of andesite angular fragments (e.g., thermal curved-fragments, TCFs) for indication of possible exposure to high heat (Cutts et al. 2019). Knapped fragments of andesite (and other volcanic rocks used as tool-stones) suspected of being heated (very likely accidental or incidental exposure) should be examined petrographically and with advanced analytical instruments (such as SEM-EDS) to investigate whether they exhibit the modifications revealed in this study. It is also possible that some volcanic rocks used a tool-stones exposed for millions of years can undergo weathering of the minerals composing such rocks. Secondary minerals produced by weathering can possess characteristics that will behave differently when heated (potentially yielding voids), compared to the primary minerals of the original rock. Textural heterogeneity present in rocks is an important parameter to consider when forensically inspecting the heating history of a tool-stone. For instance, the evaluation of distribution and shape of vesicles produced upon heating the residual glass of volcanic rocks be an important indicator at what temperature the tool-stone was exposed to (above or below T_g of the specific rock). Future research should account for the mechanisms of vesiculation in volcanic rocks that may not be triggered (in low-water residual glass) until temperatures up to 100°C above T_g (e.g., Pistone et al. 2015).

Whereas macroscopic color changes may, or may not, be useful in determining heat history of chalcedonies, the fabric of the microcrystalline quartz groundmass—often with

intergrowths of fibrous chalcedony—changes upon exposure to high heat, becoming increasingly more homogenous with a fine-grained black/white (sometimes referred to as “salt and pepper”) appearance, and losing the intergrown fibrous fabric. Further, it is noted that microfracturing becomes apparent in siliceous materials at high heat (likely perceived macroscopically as friability), and possibly indicating the dehydrating of water bound as silanole (SiOH) in the chalcedony.

Total energy exposure (i.e., temperature *and* duration) is certainly critical in achieving modifications throughout a material. This is important when transit times of fast-moving wildfires are compared to a stationary campfire. Peak temperatures of landscape fires may exceed 1000°C, but their duration is often measured in minutes. Further, the peak temperature at *ground level* is often considerably cooler compared to that at fuel-load (e.g., grass height, tree canopy, etc.; Clement 2010; Gowlett et al. 2017; Hartford and Frandsen 1992; Kremens et al. 2010; Shea et al. 1996). For example, one study conducted at Mpala Ranch, Laikipia Plateau, Kenya in mixed woodland/grassland reported ground temperatures from eighteen experimental burns never exceeded 190°C (Kimuyu et al. 2014).

3.4.3 Applications and limitations

This study highlights the value of a multidisciplinary and comparative approach to inform the heat history of a lithic artifact. Color needs to be augmented with luster and texture; color, luster and texture should be assayed macroscopically and microscopically; petrography can be corroborated by advanced analytical techniques detailing materials at micro- and nano-scale. It is important to have a database that includes unheated material as well as samples heated to variable, but standardized, temperatures and durations (approximating the variable conditions of wild and human fires at ground level). When compared to such a database, archaeological

samples may then be associated with characteristics representative of the effects of wild vs. anthropogenic fire.

While thin sections are not overly expensive, there is significant effort in developing experience using petrography and advanced high-resolution electron microscopy. Building a database of comparative samples also takes time. This study on ignimbrite or chalcedony or andesite response to heating has revealed that not all materials behave exactly the same under very similar circumstances.

Macroscopic color change did not always clearly link to distinguishing effects visible in thin section. Chalcedony that is translucent when unheated may begin to turn opaque when mildly heated, yet not reveal any significant changes in the microscopic fabric; the same chalcedony heated to extreme temperatures may not significantly change color yet show a reduction in fibrous fabric, becoming homogenously "salt and pepper" in groundmass. In the case of chalcedony, then, a more consistent indicator of exposure to high heat and duration (i.e., >500°C for >3 hours) would be noted macroscopically as friability, and microscopically as feathery fibrous intergrowths of quartz being reduced to homogenous "salt and pepper" quartz. Andesite that is dark when unheated will display the same color when heated to high temperatures and durations without showing macroscopically visible signs of textural change when, in actuality, microscopic investigation may exhibit recognizable modification.

One interpretation of these findings is that rapid field identifications of FCR may not be as accurate as previously believed. For example, color descriptions like reddened, whitened or blackened may not be a sufficiently solid indicator of the level of material heating; alternatively, they may not accurately inform the *type* of heating (stationary versus transient). Even more likely is that many artifacts that *are* anthropogenically heated have simply been missed, or "under"-

identified (i.e., they are noted as artifact, but not noted to be heated). While this could be an issue on many sites, from any time period, it may be especially true on Early Stone Age sites where the predominant stony material is andesite and other volcanic rocks, and where long-held assumptions preclude the expectation of hominin-controlled fire.

The information regarding the heat history of lithics yielded in this study positively frames the capacity of geoarchaeological research to help clarify effects of wild and anthropogenic fire. Developing new methods to more exactingly investigate *the archaeological materials that survive* in most sites (i.e., lithic artifacts) for their heat history should be of high importance to those studying the human relationship with fire, and the effect of that relationship on our biological and techno-cultural evolution.

3.5. Conclusions

Optical petrography used to ascertain the variable effects of different types of fire—i.e., natural landscape fires vs. human campfires—can be a helpful approach. Effects linked to the difference in total energy work of these distinct types of fire can elucidate whether a lithic artifact is unheated (or barely heated) or heavily affected by a controlled, high-temperature, long-duration campfire. Common rock used as knapped tools by humans and their ancestors show these variable effects, and can be used—in concert with other methods of inquiry—to argue that fire evidence on a given archaeological site was likely human-derived.

Applying optical petrography to lithic artifacts *suspected* of being derived in a human fire (e.g., thermal curved-fragments) may be of service in determining the heat-history of that artifact. Collaborative research integrating multiple methods is capable of helping address the ambiguity of FCR and related materials, as well as the issue of equifinality of effects between wild and human fires.

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Chapter 4.

EVIDENCE FOR *HOMO ERECTUS* FIRE USE: EXCAVATIONS AT THE NEW SITE FxJj20MAIN-EXTENSION-0, OKOTE MEMBER, KOOBI FORA, KENYA[3]

[3] Cutts, R.B., D.R. Braun, S. Hlubik, J. Cook-Hale, E. Garrison and J.W.K. Harris. To be submitted to *Journal of Anthropological and Archaeological Sciences*.

Abstract

With recent advances in the archaeology of fire, the debate about the timing of human acquisition of pyrotechnology and the influence that fire – and cooking – may have had on hominin evolution has become topical. The FxJj20 Sites Complex in Koobi Fora, Kenya, was among the first of "the oldest" purported evidence for potential control of fire by *Homo erectus*, ca. 1.5Mya. Since the 1970's a few other sites have been argued to demonstrate early *Homo* fire-use, while other researchers approached the topic by demonstrating how cooking might have triggered morphological changes in hominin anatomy representing access to increased calories and improved diet. Citing the dearth of evidence for widespread early adoption of fire behavior, others point to middle Pleistocene sites possessing organized living surfaces and clearly identifiable "hearth" structures as more likely indicators of pyrotechnology. We report on a new site associated with FxJj20Main – Extension 0 – that exhibits rubified sediments putatively indicative of campfire dimensions in association with Developed Oldowan "Karari Industry" tools and *thermal-curved fragments* (TCFs) that link knapped stone tools with high-energy (and long duration) fires. We present data from landscape survey that maps several such rubified features that potentially demonstrate a pattern of fire behavior at 1.5Mya.

4.1. **Introduction and Background**

4.1.1 Introduction

While it is widely accepted that fire is one of humanity's most important technologies, the timing of hominin accessioning of this tool is highly debated (Alperson-Afil et al. 2007; Alperson-Afil et al. 2009; Alperson-Afil and Goren-Inbar 2010; Barbetti et al. 1980; Barbetti 1986; Berna and Golberg 2007; Berna et al. 2012; James 1989; Brain and Sillen 1988; Brain 1993; Goldberg et al. 2010; Gowlett et al. 1981; Gowlett 2006; Gowlett and Wrangham 2013;

Isaac 1982; Roebroeks and Villa 2011; Rowlett 2000; Sandgathe et al. 2011; Sandgathe 2017; Shimmelmitz et al. 2014). Some, relying on the fact that humans are physically dependent on fire, have argued for its early use (Carmody and Wrangham 2009; Carmody et al. 2011; Wrangham and Carmody 2010; Wrangham et al. 1999; Wrangham 2017). At around 1.7-1.5 million years ago (mya), *Homo erectus* exhibits morphological characteristics—e.g., larger brain and body, smaller teeth, shorter gut—that would suggest a significant shift in diet (Aiello and Wheeler 1995; Evans et al. 2016; Organ et al. 2011; Walker and Leakey 1993). Increased carnivory is often invoked to explain these changes, but meat-eating alone may not sufficiently address questions regarding energetic requirements, and there are contemporary studies showing hunter-gatherer groups whose diets focus on plant-based foods (Aiello and Wells 2002; Koebnick et al. 1999; Shipman and Walker 1989; Wrangham and Conklin-Brittain 2003). Whether relying on vegetable foods or ameliorating pathogenic toxins in animal carcasses, cooking promotes safe processing and increases returns (Carmody and Wrangham 2009; Stahl et al. 1984; Wrangham and Conklin-Brittain, 2003).

4.1.2 Background to the FxJj20 Sites Complex

The FxJj20 Complex is a group of archaeological sites located in paleontological Area 131 in the Karari Ridge region of the Koobi Fora Formation (Figure 20). Beginning in the 1970s extensive excavations explored floodplain silts and recovered tens of thousands of lithic artifacts, mostly representing Oldowan and Developed Oldowan Industries (locally the Developed Oldowan is also termed Karari Industry; Harris 1973, 1978, 1997). These sites are within the Okote Member, which is delineated by The Okote Tuff (1.61mya) at its base, and the Chari Tuff (1.38mya) at the top (Brown and Feibel 1986). The group includes FxJj20Main, and the immediately adjacent FxJj20East; FxJj20AB is approximately 100 meters distant to the northeast

(Harris 1982, 1997). Arcing through FxJj20Main and –East were a series of nine discrete rubified sediment patches, each approximately 1 meter in diameter (Bellomo and Kean 1997; Harris 1978, 1997). These consolidated, hard, red patches were in association with the lithic artifacts and recovered bone fragments (the bone is notoriously poorly preserved in the Karari Ridge localities; Bellomo 1994). Fire was suggested as one explanation for these rubified sediments. Further analysis using thermoremanence, thermoluminescence (TL) and phytoliths implicated the presence of fire on the –Main and –East, but was not entirely conclusive (Bellomo 1994a, 1994b; Bellomo and Kean 1997; Rowlett 2000).

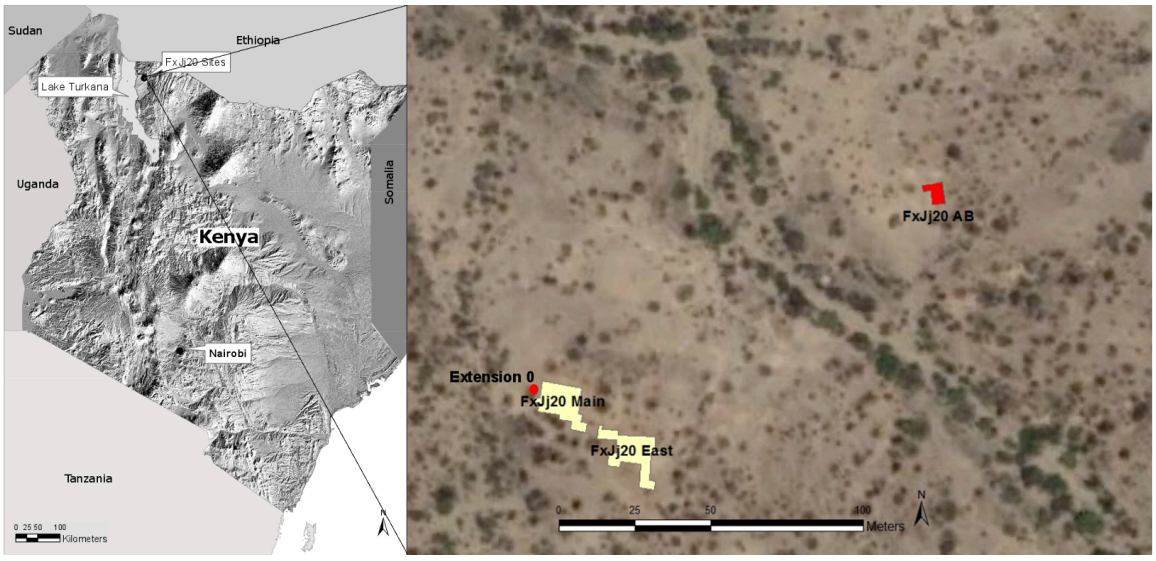

Figure 20: Location of FxJj20 Site complex. FxJj20 East and Main were fully excavated in the 1970s and 1980s; FxJj20 AB was discovered in the 1970s and was reopened for excavation in 2010. Excavation at FxJj20 AB is ongoing. FxJj20 Main – Extension 0, discovered in 2013, located outside the northwest corner of FxJj20 Main, was excavated in 2015 and 2016.

FxJj20AB was also initially excavated in the 1970s, and subsequent excavations beginning in 2010 have expanded those investigations (Hlubik et al. 2017a, 2017b). While no large rubified patches have been uncovered at –AB, small clasts of red sediments are present, being similar in color and consistency to the larger consolidated features at –Main and –East.

Extensive, interdisciplinary study of the FxJj20AB site has suggested that the sites' material is *in situ* with no significant disturbance or movement since deposition, and that the archaeological materials were likely the result of various hominin activities during one or a few occupations over a fairly short period of time. These analyses further indicate that two loci within –AB may be associated with hominin fire activity as inferred by spatial analysis (reminiscent of "toss and drop" zones; cf Binford 1983) and heated lithic, bone and rubified sediment (Hlubik et al. 2017, 2019).

1.3 Discovery of FxJj20Main-Extension-0 and further Okote Member surveys

During the Koobi Fora Field School season 2013, as excavations progressed at the FxJj20AB site, Cutts conducted surface surveys in the area of the sites complex and identified a rubified sediment feature eroding under a goat path some 15 meters to the north and west of the original FxJj20Main excavations. The archaeological nature of the feature was confirmed by other members of the Koobi Fora Research and Training Program – including Dr. Jack Harris – and the site was named FxJj20Main-Extension-0 (hereafter, Ext-0) and logged appropriately with the National Museums of Kenya in Nairobi. The rubified sediment appeared to be only partially exposed. A number of artifacts were identified, some of which were associated with the Developed Oldowan Industry (aka Karari Industry; de la Torre 2011).

Subsequent KFFS/KFRTP field seasons 2015-2016 opened excavation units at Ext-0, fully exposing the rubified feature and systematically recovering artifacts and materials from 5m^2. These included lithic artifacts, bone fragments, sediment samples and a profile of the rubified feature.

With the discovery and excavation of Ext-0, Cutts supervised KFFS surface surveys of the Okote Member sediments in Karari Area 131 (the broader locality of the FxJj20 sites

complex). In seasons 2015 and 2016 these surveys assisted researchers in identifying a number of rubified features within a radius of approximately 2km of Ext-0. These were mapped using GPS, photographs, site descriptions, pace-and-compass maps as well as aerial (drone) photography/photogrammetry. Associated artifacts and sediments were mapped, logged, bagged, labeled and curated at the National Museums of Kenya, Nairobi, by myself and other members of the Koobi Fora Research and Training Program.

4.2. **Methods**

The FxJj20 Sites Complex was first excavated by Harris in the 1970s, when materials were plotted by hand and small artifacts (<2cm) were recovered in the screen – some data is lost which affects subsequent high-resolution spatial analyses. Subsequent decades have seen progression of archaeological methods in recovery techniques, such as plotting with a total station allow for extremely accurate mapping of artifacts, ecofacts and features. Coupled with the goal of 100% *in situ* recovery of all material, this allows for a more detailed spatial analysis, which can be critical in addressing issues and questions surrounding, for example, hominin use of fire. Geographical information systems (GIS) allows the data to be visualized so that patterns more clearly resolve.

4.2.1 Excavations at FxJj20Main-Extension-0

Five units were opened in 2015 and 2016, each $1m^2$. Grid coordinates for these units is linked to the original grid for FxJj20Main and – East. Excavation followed generally standard procedures, including screening of sediment with attempts to record the original location of artifacts *in situ.* Surface artifacts were recorded and collected, and the surface of these units was sieved (2mm); each was excavated to artifact bearing depths and ultimately to sterile. This

entailed eight (8) 10cm spits across all units. Units 1 and 2 encompass the rubified feature and immediate surroundings, while units 3-5 extend to the south and east, towards the original FxJj20M. Recovery was designed to reflect the three-dimensional locations of as many pedestaled artifacts as possible, including micro-remains. Excavation tools included dental picks, Olduvai picks (a type of handled, metal pick that facilitates detailed excavation in consolidated tuffaceous silts), paintbrushes and dustpans; units were taken down in 10cm spits, except where artifact density (and feature) required 5cm spits. Artifacts ~3cm and greater were plotted with two shots on long axis to determine orientation and to inform site formation processes (McPherron 2005; McPherron 2018). Spatial data was recorded using a Leica total station and hand-held data unit operating EDM Mobile, which preserves location information to millimeter accuracy (McPherron 2005; McPherron and Dibble 2010; McPherron and Dibble 2011). Screening of sediment utilized a 2mm mesh, which helped to recover micro-remains missed *in situ*. This methodology allowed for 3D coordinates for approximately 95% of recovered materials, allowing for high-resolution spatial analysis and enabling interpretations of site activities and formation. Non-worked pebbles were collected to examine site formation processes in accordance with Schick (1986; 1987) and were sorted for size, angularity, and type of material. Pebble size classes were based on grain size as described by the Munsell (2009) soil-color chart. After recovery, documentation and photography, units were backfilled and secured.

4.2.2 Spatial analyses of excavated materials

ArcGIS was used to analyze excavation data reflecting rubified sediment and clasts, bone and stone artifacts, all of which were recorded using three-dimensional coordinates. Sieved materials (<5%) were not included in this spatial analysis. Stratigraphy of Ext-0 – indicated by the horizontal and vertical distribution of artifacts – was determined to be an extension of the

original FxJj20Main and –East. This analysis, placed in context with recent archaeological data recovered from FxJj20AB (Hlubik et al. 2017, 2019), may bring insight regarding whether the Ext-0 assemblage is the product of one or a few occupations, or the aggregation of several over long periods.

Spatial analysis was performed using ArcMap 10.7 and total station data taken during survey and excavation at the FxJj20 site. This component of the study is designed to test two hypotheses: first, that artifacts and bones mapped during survey and excavation by total station correlate meaningfully to the rubified feature interpreted as a possible hearth, and two, that these artifacts and bones were deposited in the same depositional stratum.

Total station data were stored in the form of a comma separated file (.csv format), with each point assigned a UTM and descriptive notes about the nature of the data point, the surveyor's name, and date and time. The .csv file was imported into ArcMap, assigned the correct map projection, and then converted into a point shapefile. Subsets of this general shapefile were then created using the select tool that partitioned according to data type. One shapefile, for example, was created from points designating the corners of the excavation unit, and another delineated a rubified feature; these shapefiles were then converted to a polygon format for better display. The other shapefiles included those for bone and artifacts.

Next, spatial statistical analyses determined how well bone and artifacts correlated to the rubified feature, and to elevation within the overall profile of the units. Using optimized hot spot analysis, statistical analysis assesses for correlation between features by assigned Getis-Ord G individual z score (GiZ score), and indicates whether or not a value assigned to a point feature is lower or higher than it should be in relation to another geographic feature (Getis and Ord 1992; Ord and Getis 1995). In this study, if a point is assigned a GiZ score that is lower than -1.96, this

indicates within a 95% confidence interval that this point is closer to a feature, or lower in the profile, than it ought to be if points were randomly distributed. If a point is assigned a GiZ score of 1.96 or great, this indicates within a 95% confidence interval that the point is farther from the feature or higher in the profile that it ought to be if points were randomly distributed.

The value of this analysis is that it goes a step beyond cluster analysis by detecting correlations between features across the study area. Cluster analysis such as nearest neighbors only indicates that clusters of points exist; it does not indicate if a cluster of points has any relationship to another set of features. Optimized hot spot analysis will determine which, if any, points representing bone or artifacts correlate, or do not correlate, to the rubified feature identified in these excavations. It will also suggest whether or not the heights within the profile of these materials is likely to represent the same, or different, occupational surfaces and/or depositional events.

These types of analyses inform the nature of hominin activity and potential association with the rubified feature (e.g., “toss and drop” zones, after Binford, 1980, 1981, 1983). If the rubified sediment is a ‘hearth’ – however ephemeral – the activity zone of hominin stone tool production could potentially yield a patterned concentration of artifacts in a spatial relationship with the feature that suggests associated activity areas.

4.2.3 Area 131 Survey

A walking survey of Area 131 surrounding the FxJj20 site complex extended to roughly 2km radius from Ext-0. Survey focused on exposed Okote Member sediments and aimed to locate rubified features – “red patches.” The location of each was recorded using global positioning satellite (GPS) data. The overall dimensions, length and width, as well as location of surrounding materials (lithic artifacts, bone) were recorded with a tape measure, and photographs

documented these features and materials. An aerial image of the survey area was recorded using a drone, and the spatial data of the rubified features and associated materials was mapped using ArcGIS. This data was analyzed for patterns and trends that might inform interpretations of the features. Any materials recovered during the survey were located using GPS, described, photographed, bagged, labeled and curated at the National Museums of Kenya, Nairobi.

4.2.4 Thermal curved-fragments and review of NMK FxJj20 assemblage

Previous experimental work identified an angular fragment produced when knapped stone flakes are subsequently fractured in campfires. These thermal curved-fragments (TCFs) are recognized by a peculiar symmetry – an "evenness quotient" (EQ) – characterized by an evenness of thickness *and* width along the curvilinear length of the piece (Cutts et al. 2019; Hlubik et al. 2019). Like "potlids" – spalled fragments recognized as being produced by exposure to fire – TCFs could be indicative of the association of human activity (e.g., stone tools) and fire.

A review of collections at the National Museums of Kenya, Nairobi, focused on the angular fragment assemblage of FxJj20Main and –East, sought to identify pieces that conformed to the characteristics of TCFs. Fragments so identified were measured according to the protocols outlined for quantifying TCFs and analyzed for potential association with fire (Cutts et al. 2019).

4.3. Results and Preliminary Discussion

4.3.1 Archaeological excavations – artifacts, feature and site formation

Upon discovery of Ext-0, a number of Developed Oldowan (Karari Industry) artifacts were recovered from the surface. These included a basalt "hammerstone" exhibiting fracture patterns and damage consistent with both stone tool production (battering; aka "pounded piece")

and heat-damage (i.e., “pot-lidding”). The actual potlid detached piece was discovered in close association (ca. 20 cm distant); this angular fragment potlid successfully refits to the larger hammerstone (Figure 21). Also recovered from the surface during discovery of Ext-0 was a Developed Oldowan (DO; locally aka Karari Industry) chopper (Figure 22). Developed Oldowan infers a transitional phase (towards Acheulean) from flaked (often unifacial) Oldowan cores and choppers to bifacial working of edges.

Figure 21. Battered basalt hammerstone with associated potlid fracture (refit). Recovered from rubified feature FxJj20Main-Extension-0 surface collection. Scale = 1cm.

Figure 22. Green ignimbrite Developed Oldowan chopper. Ext-0 surface collection. Scale = 1cm.

The basalt hammerstone exhibits pitting and battering commensurate with being used in percussive activity. The potlid piece refits to the hammerstone and neither exhibits the "peeling" aspect that basalt will form during natural (weathering) exfoliation. Found approximately 20cm apart, both were recovered eroding out of the rubified Ext-0 feature. The ignimbrite chopper is bifacially worked, reflecting the "developed" aspect of the Developed Oldowan (Karari Industry) noted in many artifacts recovered from the FxJj20 Sites Complex.

During the 2015 and 2016 field seasons five (5) 1m2 units were opened, exposing the entirety of the rubified feature and extending to the south and east towards the 1970s FxJj20Main locality. Excavations revealed the majority of the rubified feature was undisturbed (~80% intact *in situ*) by the eroding goat path. The FxJj20 Sites Complex is known for recovered bone being highly degraded, often to the point of indeterminate identification, and this was true of recovered bone (n=52) and teeth (n=2) from these Ext-0 units. Lithic artifacts recovered (n=89) were also

consistent with other localities in the FxJj20 sites, being primarily basalt flakes with associated exhausted cores, one of which was identified as a "Karari scraper."

Table 7. List of recovered materials from FxJj20Main-Extension-0.

Ext-0 Materials	Count
Core	9
Flakes	61
Angular Fragments	19
Pebbles	420
Hammerstone	1
Bone	52
Tooth	2
Total	564

The incidence of recovered bone was noticeably higher in the two units (1 & 2; Figure 23) that encompass the rubified and hardened sediment, while the volume of lithic artifacts are concentrated in units 3-5, approximately 1-2 meters from the reddened patch. Optimized Hot Spot Analyses of lithic artifacts indicates non-random association of artifacts to each other and to the rubified feature, indicating the likelihood of a behavioral aspect to deposition (Figure 24). The lithic artifacts are commensurate with a reduction sequence wherein largest (i.e., most useful) flakes are not strongly represented in depositional sequence. The observed artifact distribution patterns will be explored further in Discussion.

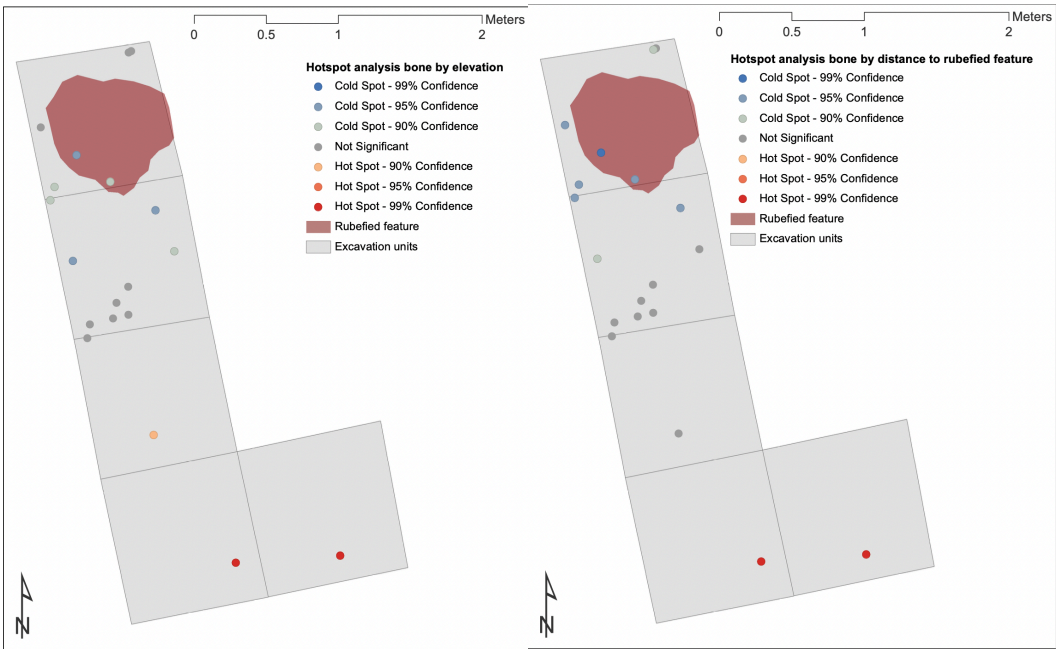

Figure 23. Optimized Hot Spot Analysis (OHSA) of distribution of bone in Ext-0 excavations by elevation (left) and distance (right) using the rubified feature as reference point.

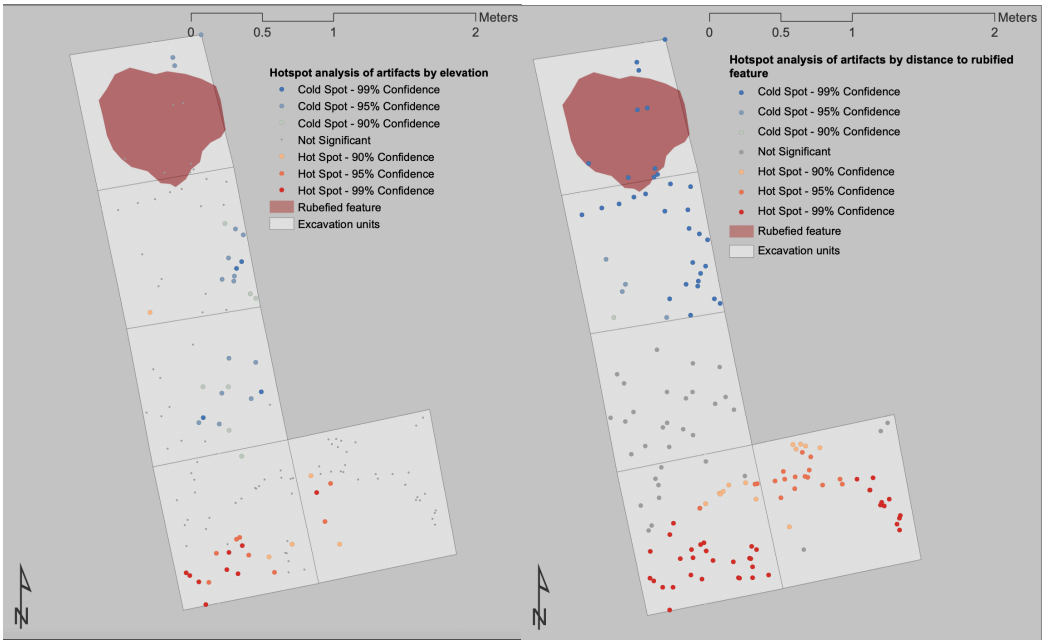

Figure 24. Optimized Hot Spot Analysis (OHSA) of distribution of lithic artifacts in Ext-0 excavations by elevation (left) and distance (right) using the rubified feature as reference point.

Other than the rubified feature (Ext-0, units 1 & 2), no other similarly hardened or discolored sediments were revealed in units 3, 4 or 5. However, very small clasts (<1cm) of ochre were noted in units 3-5. Flakes greater than 3cm were significantly more represented in units 3-5, approximately 1-1.5m distant from rubified feature.

The rubified feature was isolated in excavation, determined to be approximately 1 meter in diameter, and then profiled. The reddened sediment of the feature is noticeably hardened, compared to the tuffaceous silts surrounding it. Using both color and texture, the feature was mapped and determined to exhibit a “lozenge” or “basin” shaped morphology, in profile (see Figure 25, and compare to Aldeias et al. 2016). This basin shape – where the edges of the reddened (and hardened) sediment are shallower and the middle is deeper – is reminiscent of the profile patterns of experimental fires and their underlying (differentially heated) sediments. The edge depth of reddened sediment varies from 1-2 cm deep, while the center of the rubified sediments penetrates to around 8cm. Further discussion of Ext-0 rubified feature will be explored in the next section.

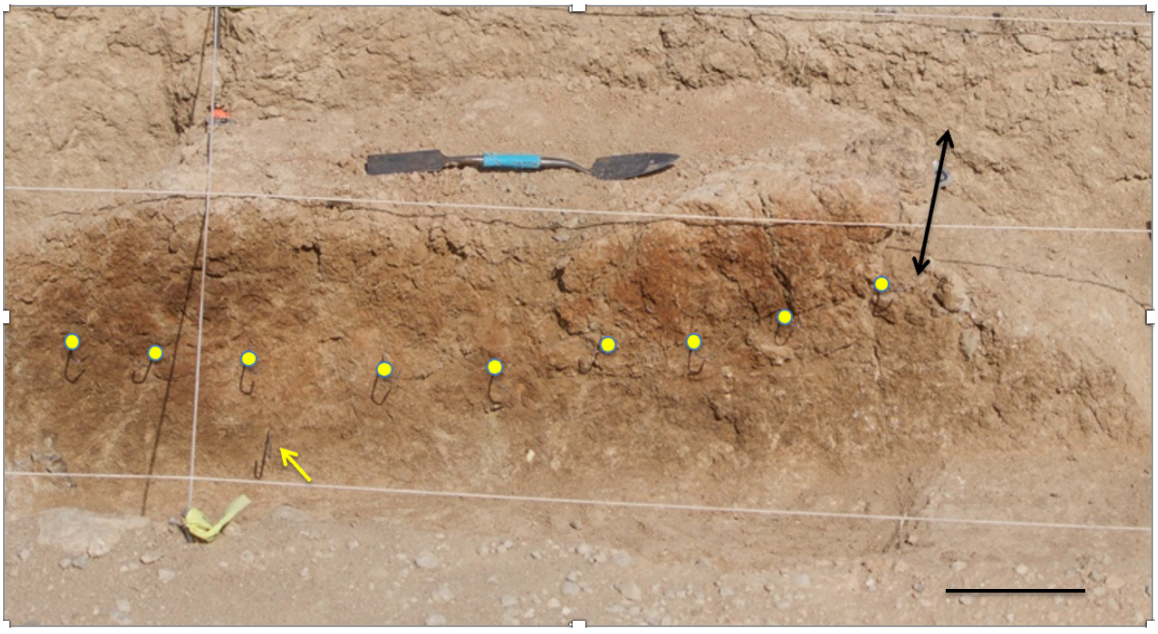

Figure 25. Profile of Ext-0 rubified feature. Black arrows indicate erosion by goat path, north end of feature. Reddened, hardened "basin- or lozenge-shaped" sediments in profile were marked by pin (here highlighted by yellow dots), exhibiting shallow edges (~2cm depth) and deeper center (~8cm). Trowel and square (26.2cm length) points north. Scale is 10cm.

The investigations at Ext-0 do not support the interpretation that the site was disturbed to any great extent by post-depositional processes. Excavations did not yield evidence of any large bioturbative agents such as tree roots or rodent burrows. Analysis of artifact size profiles and pebble class size and angularity (Tables 8 and 9) suggest that a low-energy water flow buried the site under silts that subsequently underwent natural soil formation processes. A high frequency of smaller pieces suggests low energy depositional environment with little or no sorting or winnowing after initial deposition (following Schick, 1986, 1987). There is no apparent preferred orientation of the artifacts within the site, further supporting the interpretation that Ext-0 is essentially undisturbed from original deposition.

Table 8. Distribution of pebbles by size class (after Munsell soil-color chart).

Size Class	Count	% of Total
1-2mm	15	3.6
2-5mm	170	40.5
5-10mm	176	41.9
10-15mm	18	4.3
>15mm	41	9.8
Total	420	-

Table 9. Distribution of pebbles by angular class.

Angle	Count	% of Total
Angular	12	22.2
Sub-Angular	19	35.2
Sub-Rounded	18	33.3
Rounded	5	9.3
Total	54	-

4.3.2 Area 131 survey

A total of 25 "new" rubified patches were identified during the landscape survey of Okote Member outcrops surrounding the FxJj20 Sites Complex. Figure 26 shows the location of 19 of these reddened patches, while the remaining 6 are located too close to the excavation(s) localities (red box on map) to be clearly resolved. Of these newly identified rubified features, 83% exhibited associated lithic material, with 66% having basalt flakes present, 16% with chalcedonic artifacts and 66% having (indeterminate) bone.

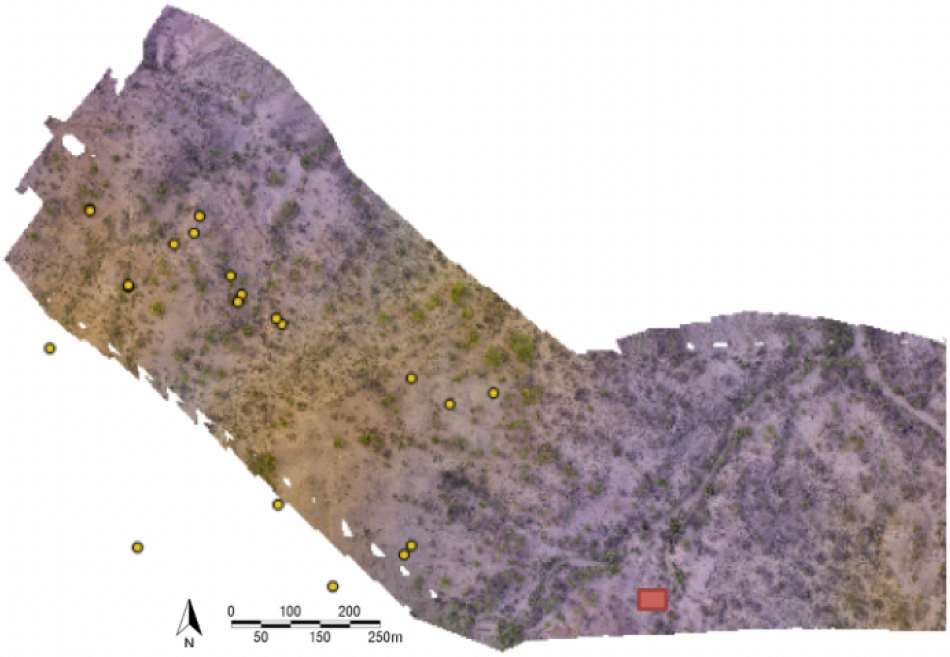

Figure 26. Area 131 landscape survey map of rubified patches. Yellow dots indicate locations of 19 identified rubified features to the north and west of FxJj20 Sites Complex (red rectangle), where a further six (6) rubified patches were also recorded. Note the tendency for patches to exhibit clustering of two or three in close proximity, as well as the overall arcing pattern of distribution across the landscape that may be associated with a paleochannel.

The rubified features are typically between .75m and ~1.25m across. When mapped these rubified features seem to show some interesting patterns. The patches can occur singly, but there are six clusters of at least two patches each; further the landscape distribution seems to exhibit two broader "arcing" patterns – one comprised of five patches (upper left of map image) oriented SW to NE, while the other is comprised of up to eleven patches (across the middle of the map) oriented more E-NW, and potentially intersecting at the NW margin with the other "arc." These rubified features will be discussed further in Discussion.

4.3.3 Review of NMK FxJj20 artifacts – TCFs

After clarifying the nature of *thermal curved-fragments* (TCFs), a review of the FxJj20 Sites artifact assemblage housed at the National Museums of Kenya was conducted. Of particular interest were artifacts having been originally described as "angular fragments" (TCFs being a peculiar type of angular fragment). Out of ~1500 angular fragments in the FxJj20Main and -East collection (found *in situ* during 1970s excavations), fifteen potential TCFs were identified (refer to Figure 27 for examples). These were measured and are statistically consistent with curvilinear characteristics of experimentally-derived TCFs (Cutts et al., 2019; Hlubik et al. 2019). Experiments have shown that TCFs are not necessarily produced in large numbers, being an incidental (or accidental) interaction of knapping debitage with campfires, and basalt debitage is less likely to thermal curve-fracture than chalcedonic or ignimbrite types (FxJj20 collections are ~90% basalt). Unheated knapping debitage is expected to significantly outnumber FCR in most assemblages. Figure 8 exhibits a selection of both archaeological (potential) and experimental TCFs. The TCF recovered from surface collection on Ext-0 (2015 season; Figure 28) is commensurate with experimental TCF characteristics.

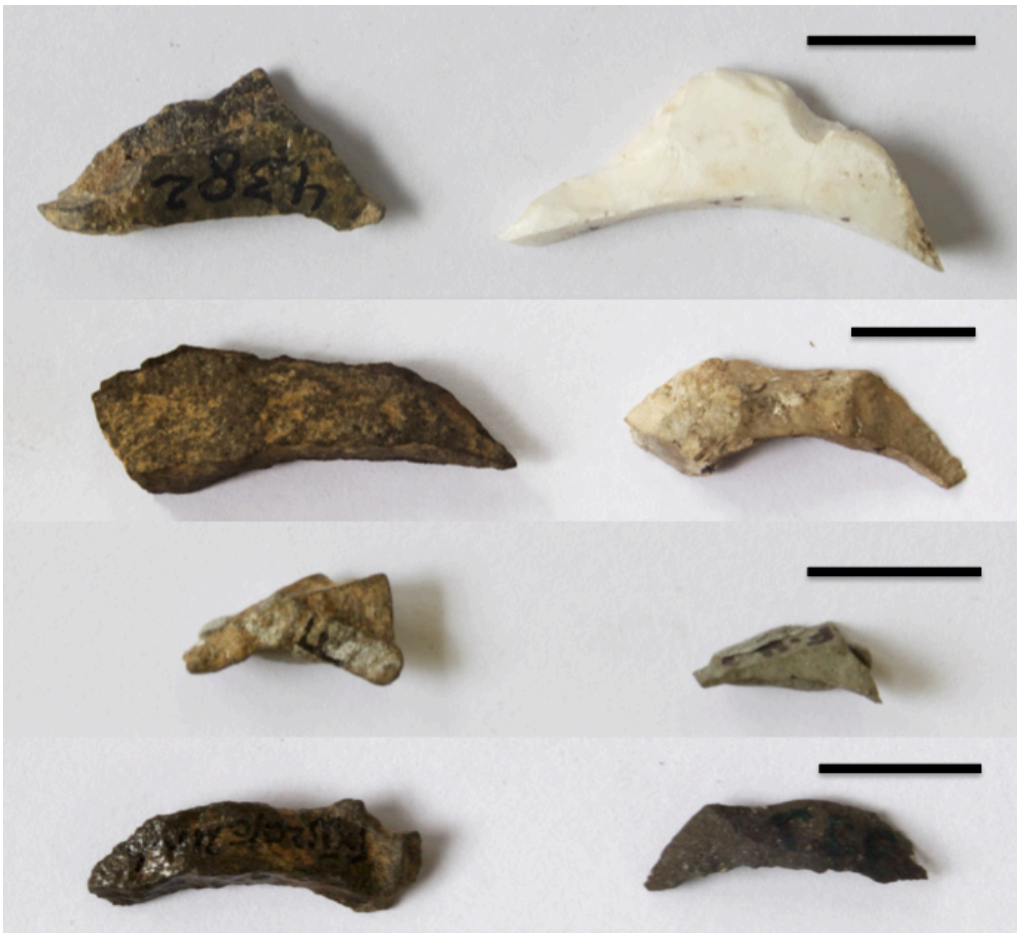

Figure 27. Selection of archaeological (potential) TCFs (left) from angular fragment collection of FxJj20Main and -East, and experimentally-derived TCFs (right). Scales = 1cm.

Figure 28. Potential TCF-type angular fragment from FxJj20Main-Extension-0. Recovered in surface collections approximately 1.5m from rubified feature.

4.4 Discussion

While the results of this study – excavation, survey and museum artifacts review – provide insights suggesting the possibility of hominin-controlled fire by *Homo erectus* ca. 1.5Mya, we cannot assert unequivocally that such was the case. What is more certain is the benefit of this work to the archaeology of fire: the value of an interdisciplinary effort, the importance of focusing on recovery techniques, and the awareness that criteria used by many archaeologists to infer undisputed evidence of fire on an archaeological site may be biased towards behavior(s) (i.e., formalized hearth-settings, etc.) that may or may not be representative of ESA hominins, nor even of modern-day hunter-gatherer foragers.

There is also the issue of Type II statistical errors, where a null hypothesis that is false is accepted as valid; for example, assuming that because most remains of fire do not preserve well in open-air sites of great antiquity, therefore archaeology may never be able to determine when fire was first accessioned into hominin behavioral repertoire. Further, when one does not know what one is looking for, it can lead to not seeing it when it is present…such seems to have been the case prior to the identification and quantification of *thermal curved-fragments* (TCFs). Indeed, other recent experimental work advancing understanding of fire-cracked rock (FCR) has shown that even basalt and andesite could express microscopic textural and mineralogical changes when exposed to extreme heat and long duration fires (Cutts et al., 2021, *under review*). In that so much of the artifact assemblages (~90% in many cases) from ESA hominin sites – especially in east Africa – are comprised of basalt/andesite, the presence of possible TCFs in the excavated materials of the FxJj20 Sites Complex deserves further investigation (e.g., petrographic analysis). The ongoing work at the FxJj20 Sites Complex frames the complications and potential mismatch between methods investigating the presence of (human) fire on archaeological sites and the nature of sites that currently predate the purported "undisputed" beginnings of culturally curated fire in human societies.

The nature of the rubified feature – overall dimensions and lozenge shape in profile – in addition to the distinctly oxidized and hardened aspect of the feature sediment are reminiscent of the changes that occur underneath controlled campfires (see Aldeias et al. 2016). Degraded bone associates more closely with the feature, while lithic artifacts indicate non-random distribution in association with the feature. These lithics are located predominately ~1.5-2 meters distant, and whose spatial configuration is indicative of an activity area (knapping or working with knapped flakes). The observed artifact distribution in the Ext-0 units is representative of Binford's (1983)

"drop" and "toss" zones, in this case potentially near a campfire. Lithic artifacts recovered encompassed angular fragments, small and large flakes, and cores, as would be expected from a full reduction sequence, yet refit was not possible with fragments recovered, potentially inferring the removal of useful flakes from the sequence.

The presence of TCFs from FxJj20M-Ext-0 and excavations adjacent to Ext-0 (-Main and -East) lend support to the interpretation of these rubified features represent heated sediments. This work at FxJj20Main-Extension-0 offers significant evidence that the presence of fire was in association with hominin activity at this locality. This coincidence of fire and hominin behavior does not necessarily imply that these hominins were *controlling* the fire, nor intentionality (that they were able to produce (create) fire at will). However, this work adds to a growing body of evidence indicating associated hominin behavior with fire in the Early Stone Age.

The results of surface survey of newly identified rubified features in Area 131 provides insight into the possibility of hominin landscape activity. Initial assessment of the arcuate patterns inferred by mapping the distribution of these reddened patches suggests a potential association with riverine paleochannels – that hominins in this area were utilizing edge environments of gallery forests along rivers or creeks as bases for activity around campfires (e.g., tool production, butchery, potentially cooking meat prior to consumption). The consistent association of lithic and bone artifacts with these rubified features, and the clustering nature of the features, also suggests a connection to hominin behavior. The ancient environment in this area did include two rivers with open woodland and grassland areas. It may be that the arcs followed the riparian systems, as these locations would have provided hominins with ideal resource-rich conditions. That these rubified features are remarkably consistent in elevation (+/- ~1.5m) within the Okote Member is perhaps suggestive of some aspect of the ancient landscape

driving locational behaviors. The availability of wildfire on ancient landscapes would provide access to fire for early hominins, who likely would have experienced fire on a regular basis. Studies investigating long term trends represented in terrestrial cores suggest that proxies of past habitats may assist in detailing models reconstructing the incidence of fire on ancient landscapes (Campisano et al., 2017; Glikson 2013; Goldberg et al. 2017). Work by Pruetz and colleagues documenting fire-behavior in chimpanzees offers glimpses into the possibility of homologous behavioral phenotypes of these great ape clades (Parker et al. 2016; Pruetz and LaDuke, 2010; Pruetz and Herzog, 2017). One of the adaptive advantages of fire is its ability to provide protection from predators (Bellomo, 1994).

While intriguing, the results of this survey are preliminary. It remains possible that these rubified features result from some as-yet unidentified process, with alternative explanations potentially including ancient burned termite mounds or tree stumps, and even ancient springheads. More intensive investigation is required to develop clearer understanding of how these reddened patches are formed, and what their behavioral implications for hominins may, or may not, involve.

4.4.2 The future of fire research

Sites such as the FxJj20 Complex – beyond advancing the archaeology of fire – continue to hold potential for future study. For example, there is significant overburden yet separating Ext-0 from the original -Main locality. The living surface of Ext-0 and -Main can be reasonably assumed to be the same horizon (based on elevation, a gently undulating surface); if so, there are approximately 20m^2 of potential *in situ* material that could be excavated just at this location.

The excavations at Ext-0 recovered a micromorphology (MM) pillar and thermoluminescence (TL) sample, neither of which have yet been fully assayed. Continued

analysis of these important remains will undoubtedly provide new data on the question of hominin-controlled fire on these sites. And indeed, future research should involve sampling the many newly identified reddened patches via excavation, micromorphology and TL. Further chemical and magnetic analysis of the feature in FxJj20M-Ext-0 could further support that feature is a potential hearth. Proximity to the FxJj20Main site suggests it would show similar traces as in Bellomo (1994).

4.5 Conclusion

We have reported here several interacting lines of evidence that, taken together, infer the possibility of hominin use of fire at 1.5Mya. New excavation data, landscape survey and actualistic studies presented herein build upon earlier work suggesting that humans began accessioning fire into a behavioral repertoire during the Early Paleolithic (African ESA). Since the 1970s the FxJj20 Sites Complex at Koobi Fora, Kenya, has been argued to potentially exhibit archaeological remains that associate the Developed Oldowan – or Karari Industry – with the use of fire. Specifically, we have documented a newly excavated rubified feature – FxJj20Main-Extension-0 – that is interpreted as the ephemeral remains of a campfire hearth, in association with Developed Oldowan artifacts and TCFs. The spatial distribution of artifacts indicates a hominin activity area that was not heavily disturbed post-deposition. Behavioral indicators in and around the hearth could suggest some degree of hominin control over the fire, or at least that in some way their behavior was based around it. Further, we have presented landscape survey data potentially inferring hominin-fire behavior being associated with ancient landscape features. These rubified patches maintain consistencies in that they are discrete, isolated, circular areas consisting of hard, reddened sediment. They are noticeably different from the surrounding

tuffaceous silt. The distinct clustering and arcing patterns, as well as the associated bones and lithics, suggest the potential association of early hominin behavior with these rubified patches.

As the archaeology of fire continues to develop and mature, advances will include refining archaeological proxies/evidence that clearly indicate *human-control* (and intentionality). Further, establishing the 'when' of early human use of fire will not rely on one location or site; rather it will involve consistent indicators of manipulated combustion in direct association with living surfaces and activity areas. Pyrotechnology is a complicated business, whose lines of evidence range from manufacture of adhesive mastics to using fire for hunting across a landscape (Bliege Bird and Bird 2015).

If cooking and the use of fire did, in fact, have a major influence on the biological evolution of the genus *Homo*, this could be indicated by a growing body of ephemeral sites (more than just the rare but well-preserved cave locations) that clearly exhibit spatial association of artifacts and fire (Sandgathe and Berna 2017, and others in that volume). In particular, TCFs can be another straightforward macroscopic indicator that human-fire may be present on a site, encouraging researchers to refine their approach to accommodate fine-scale investigation(s) and high-recovery techniques. At the FxJj20 Sites Complex, this complementary approach has yielded the possibility that multiple archaeological localities in this area exhibit a suite of evidence strengthening the hypotheses that early fire use may have promoted biological and behavioral adaptations in the human lineage (Wrangham et al. 1999; Wrangham and Conklin-Brittain 2003; Wrangham and Carmody, 2010).

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Chapter 5.

CONCLUSION TO THE DISSERTATION

5.1 Advancing the archaeology of fire

The research presented in this dissertation demonstrates the value in pursuing novel, experimental, methods to approach challenging questions in archaeology, in particular the origin of the human use of fire. While most remains of fire are ephemeral and do not persist well in the archaeological record, by focusing on an artifact class – lithics – that is not only widespread in archaeology but also *durable*, it has been shown that archaeology does have the potential to segregate the effects of wildfires from those of anthropogenic campfires. Geoarchaeological techniques can be used to explore the 'heat-history' of artifacts and features in archeological sites. The following is a list of evidence reported in these papers that support this claim:

1. Thermal-curved fragments (TCFs) are a specific subset of fire-cracked rock and angular fragments that are indicative of the interaction between human/hominin stone knapping (tool-making) with temperatures and durations associated with campfires (vs. wildfires).
2. TCFs are quantifiable, and their presence in an archaeological assemblage likely indicates the presence of human controlled fire.
3. TCFs are unlikely to be produced as a by-product of only stone-knapping, without exposure to fire; TCFs are unlikely to be produced by rapidly moving landscape fires.
4. Commonly used, subjective, terminology applied by archaeologists – e.g., reddening, blackening, whitening – are not always valuable in determining the heat-history of an

artifact; texture and luster may be more indicative of heat-exposure of stone tools and debitage.

5. Petrographic analysis of thin-sectioned lithic artifacts can yield information on the heat-history of that artifact; some classes of common tool-stone (e.g., chalcedony) have consistent modifications at particular temperatures and durations.
6. Combining TCF studies with petrographic analysis could be very helpful in determining the heat-history of an artifact, as well as ascertain whether evidence on a given archaeological site is a product of anthropogenic or natural wildfire.

This research has shown that the detection of anthropogenic fire on even ephemeral, open-air archaeological sites is possible. While beneficial, the requirement of confined, stone-lined hearths, ash-lenses and charcoal to validate anthropogenic fire may not be available on many sites; having the ability to infer the presence of human-controlled fire via the identification of specific lithic artifact morphologies is extremely valuable.

5.2 Behavioral implications for human evolution

The presence of TCFs along with the rubified feature exhibiting "basin" shaped profile in direct association with Developed Oldowan "Karari Industry" artifacts presents a significant argument that *Homo erectus* was interacting with controlled fire on this locality. The FxJj20 Sites Complex, including this research (FxJj20Main-Extension-0) and recent work at FxJj20AB comprise the current oldest evidence of the hominin control of fire. Evidence of major post-depositional disturbance on Extension-0 is lacking, and the spatial distribution of artifacts is suggestive of an association between the lithic artifacts and the rubified feature.

This work indicates that Wrangham's (1999) hypothesis regarding the role that fire and cooking may have had on the morphological changes exhibited by *Homo erectus* around this time in hominin evolution merits further consideration. While complex behaviors are notoriously difficult to ascertain in archaeological assemblages – especially those from Early Stone Age open-air sites – this work suggests that an interdisciplinary approach using multi-proxy lines of evidence can yield significant insights into the evolution of our hominin ancestors.

5.3 Future directions in research

The future of research in the archaeology of fire seems to require advancement along four fronts:

1. Continuing to develop new methodologies that quantify the *intentional, controlled* aspect of human-fire interactions;
2. Exploring the distinctive *three (3) horizons* of human-fire behavioral ecology – A. *accessioning* fire into the hominin behavioral repertoire; B. various human lineages increasing their abilities to *keep fire alive* (coal-carrying, torching, landscape-management, etc.); and C. inventing the multiple (>8) pyrotechnologies that *create* fire-at-will;
3. More thoroughly integrate methodology with site investigation so as to accurately assess human application of pyrotechnology over time, and space; and
4. Continue to locate and investigate new sites that produce data informing on the ever-increasing interactions of humans with fire.

With regards to developing new methodologies that quantify the human-fire interface, I can definitively state that I have discovered yet *another* quantifiable angular fragment that is

indicative of the interaction of humanly knapped stone tools and hot, long-duration fires. I have tentatively described these as “caltrops” due to their distinctive morphological characteristics that resemble that medieval weapon. I anticipate that incorporating 3-D imaging technology will significantly advance the ability to link specific FCR morphologies to “temperature/duration” – and hence increase archaeological confidence in ascertaining anthropogenic fire.

It has been my experience during the course of this research that a discrepancy exists in the archaeological understanding of the nature of fire (e.g., attained vs. sustained temperatures, energy-work of fluctuating fire temperatures, effect of fire on andesites and basalts, etc.). I intend to investigate and clarify this challenging issue, especially as it pertains to such issues as site-specific (re: species-specific) “quality” of fire. Examples could include differential temperatures associated with predominant fuel-types, limitations of open-air vs. cave/shelter settings, and the like.

Future research into the archaeology of human-fire interactions must also integrate with the broader disciplines of geology, geography, fire ecology, among others. In particular, studies of ice- and sediment-cores (especially lacustrine) can illuminate cycles of increased landscape fire – potentially influencing, or influenced by, humans and their use of fire. Continuing to identify the nature of fire-affected phytoliths, fungal spores, and the residues of cooked-foods in dental calculi will invariably drive the investigations of the human-fire interface. Even the ongoing studies of *aDNA* can help further our understanding of the human fire relationship, as some studies are showing promise for determining which genes promoted the “human tolerance” for continued exposure to smoke. As I have demonstrated in this document, examining lithologic and petrographic change using instrumentation has great utility. SEM-EDX, Electron

microprobes, STEM, etc., will remain mainstays in the attempt to detect and characterize humanly made fire in prehistory.

It is my goal – potentially as early as the 2022 field season – to expand the excavations at Ext-0, to continue the landscape surveys of the Okote Member fossiliferous sediments in Area 131 (among others), and to integrate these archaeological findings among regional studies (East and South African) of hominin fire usage. I intend to continue to integrate experimentation, archaeological investigation, and geoarchaeological research to further our understanding of the dimensions of the human-fire interface, as it continues to assert an enduring technological influence.

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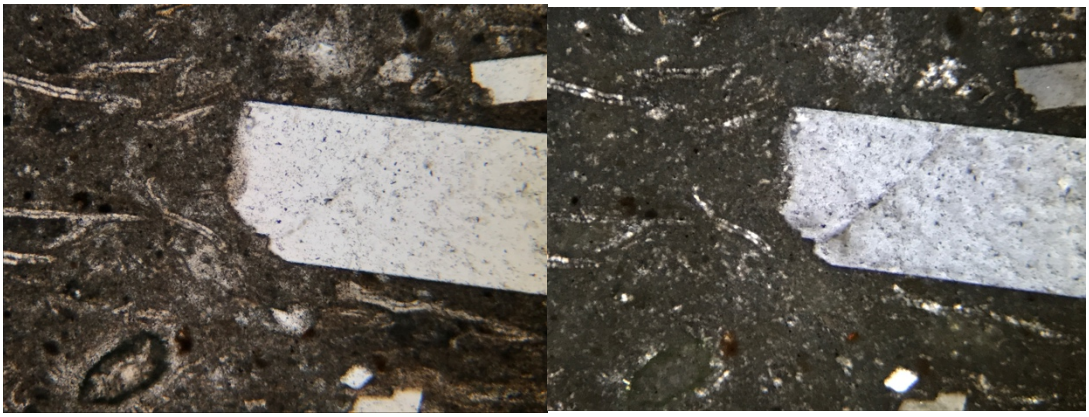
APPENDIX A

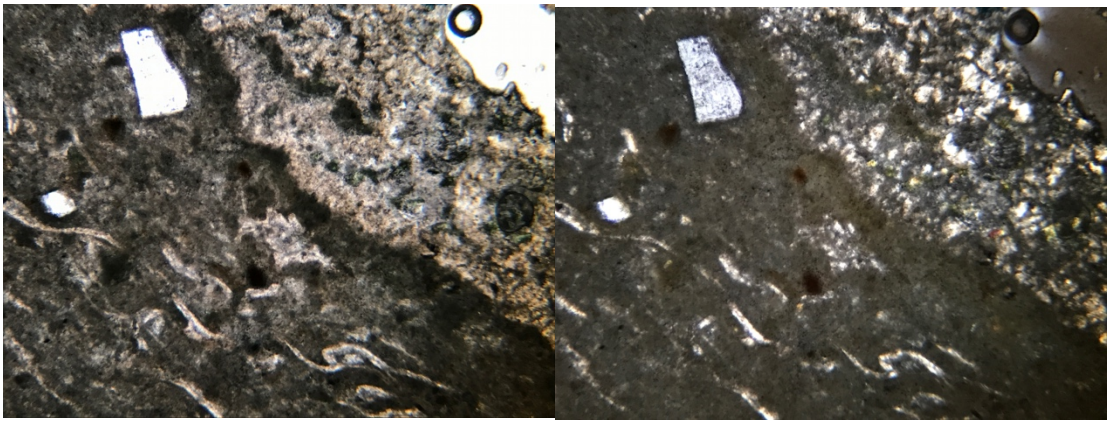
Selected macroscopic and microscopic thin section description of samples mentioned in this study. Original sample labels retained (e.g., B, B1-B5). Complete list of samples in this study range from A – V; not all samples are reported in article text. NOTE: first lines under individual samples are macroscopic descriptions after heating; microscopic descriptions always begin after phrase 'thin section'.

B. Green Ignimbrite

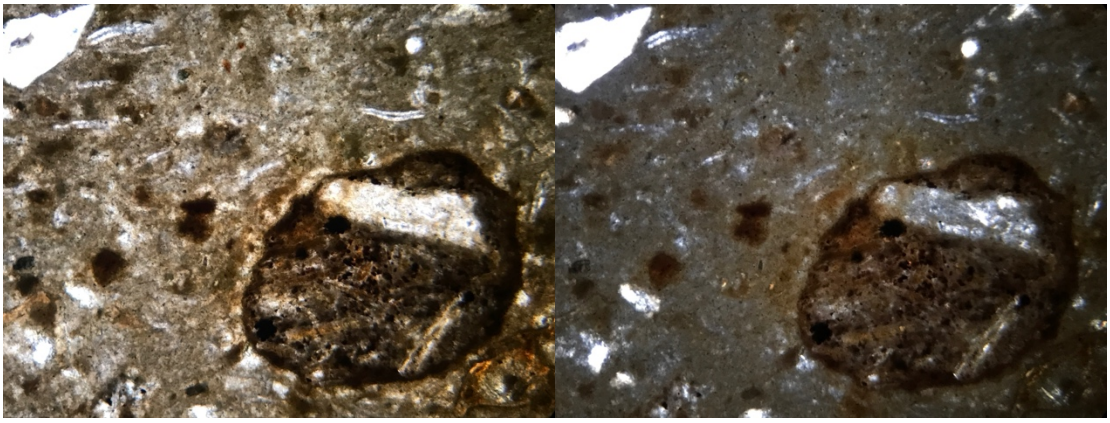
Field identification as **East African Green Ignimbrite**. Greenish-grey fine-grained rock exhibiting conchoidal fracture. Dull luster, lightly mottled with yellow and dark green crystals, occasionally showing sparkle.



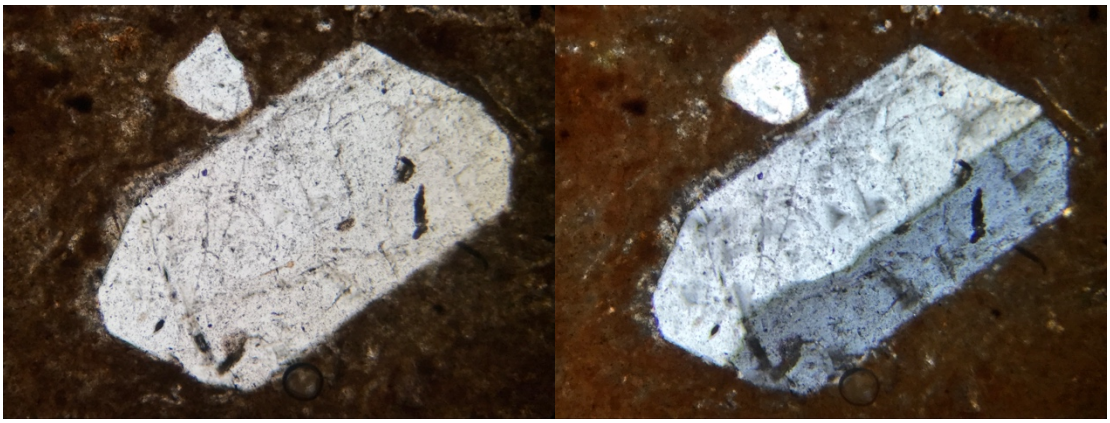
B1. Unheated thin section consistent with rheomorphic lithified ignimbrite. Flow banded eutaxitic lapilli tuff with groundmass of welded glass shard, interspersed with flattened pumice clasts and phenocrysts of biotite, quartz and feldspar. Biotite sometimes hexagonal in cross-section, showing one cleavage, moderate to high relief, strong pleochroism, birds-eye extinction and 3rd to 4th order birefringence of brown, red-brown and brown-green colors. Quartz grains are colorless, show no pleochroism, low positive relief with low order birefringence white tinged with yellow (0.009), no cleavage, no twinning but does show undulatory extinction. Alkali feldspar crysts appear colorless in plain polarized light, showing no pleochroism, low 1st order birefringence in grey color and exhibiting simple twinning with 90° cleavage.



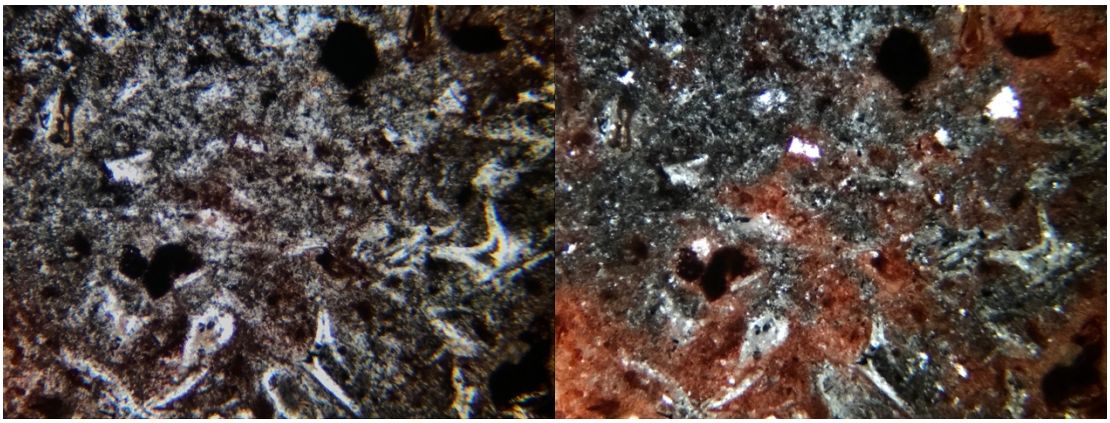
B2. 250°C, 3 hours. No visible color or structural change from B1. Thin section consistent with B1 – groundmass of flow banded welded glass shard interspersed with clasts of flattened pumice, biotite and feldspar.



B3. 500°C, 3 hours. Dark grey-brown, mottling includes white and red crystals with higher incidence of sparkle; friable. Thin section consistent with B1, B2 – groundmass of flow banded welded glass shard interspersed with flattened pumice clasts, biotite and feldspar.



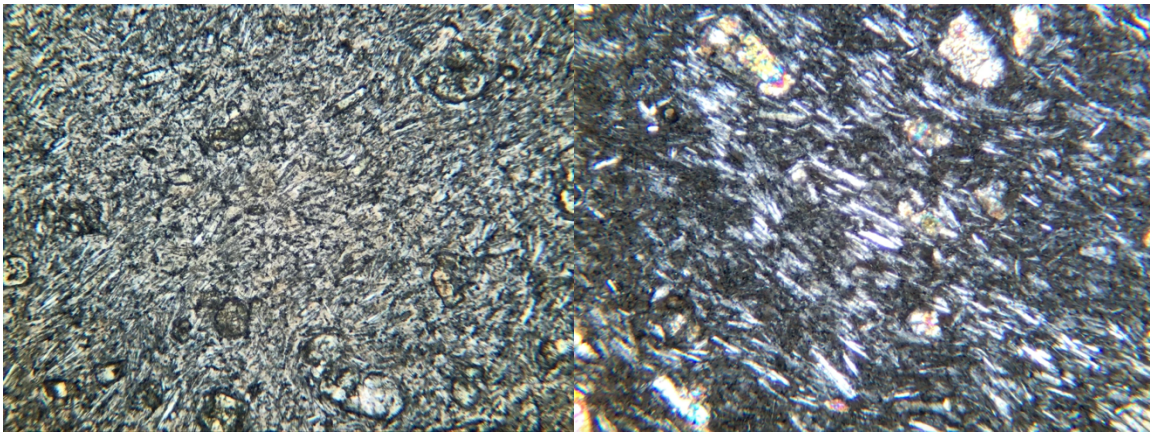
B4. 750°C, 3 hours. Dull red-brown; mottling is lessened, but present. Thin section glass shard groundmass exhibits reduced flow banding (disorganization). Clasts of biotite, feldspar and flattened pumice persist.



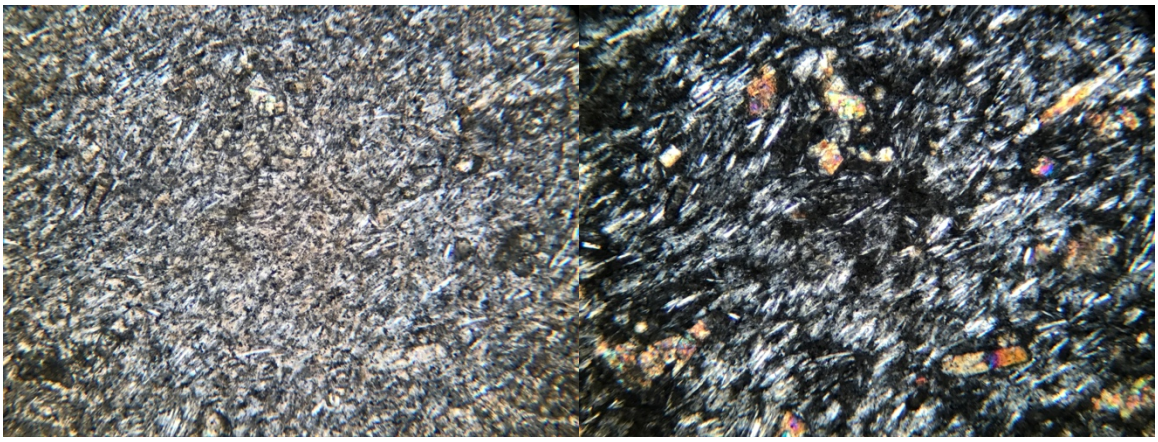
B5. 1000°C, 3 hours. Oxidized to deep red-brown, flat luster. Mottling more pronounced showing white and black inclusions. Friable and crumbling. Thin section groundmass of welded glass shard has reduced flow banding. Phenocrysts of feldspar, biotite present.

D. (Basaltic) Andesite

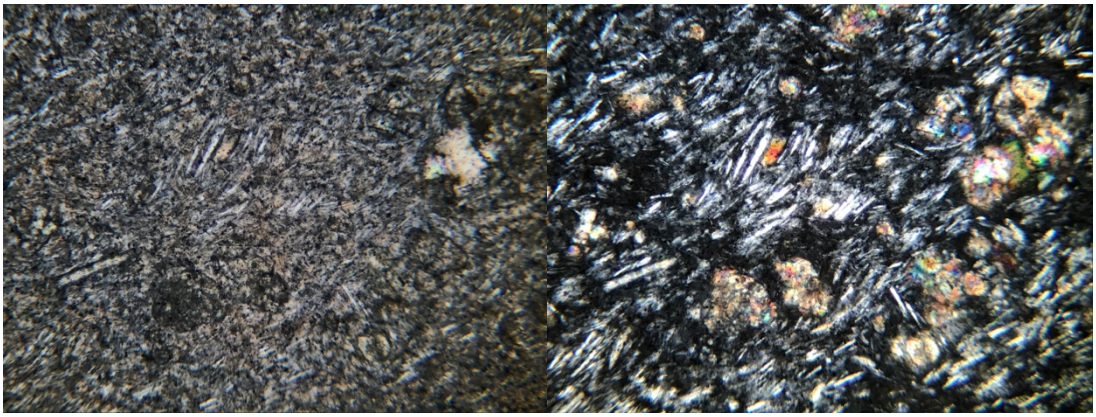
Field identification as **East African Basalt.** Laboratory identification as andesite. Black fine-grained rock exhibiting conchoidal fracture. Dull luster; hardness 6.



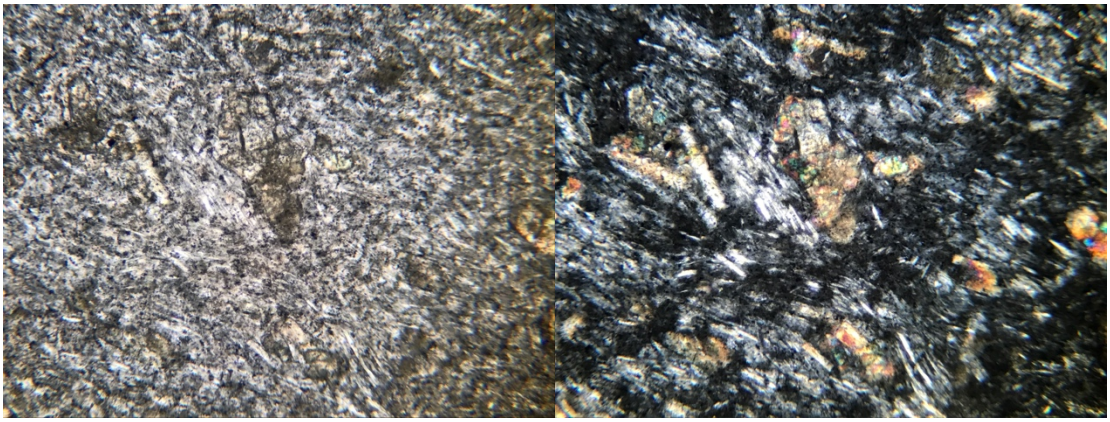
D1. Unheated thin section shows fine-grained groundmass of heavily flow banded plagioclase lathes exhibiting twinning, interspersed with porphyritic phenocrysts of biotite and pyroxene. Interspersed loosely with small, opaque, cubic inclusions of magnetite.



D2. 250°C, 3 hours. Consistent with D1 – black, fine-grained, dull; no apparent structural changes. Thin section consistent with D1 – flow banded fine-grained plagioclase groundmass interspersed with pyroxene and biotite clasts, as well as opaque magnetite microcubes.

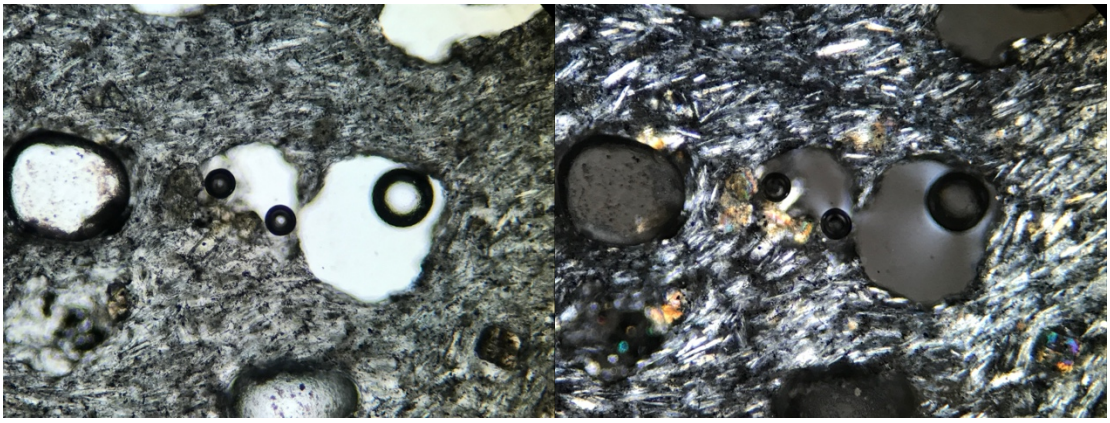


D3. 500°C, 3 hours. No visible or apparent structural change from D1, D2. Thin section consistent with D1, D2 – fine-grained flow banded plagioclase lathe groundmass interspersed with pyroxene, biotite.



D4. 750°C, 3 hours. No visible or structural change. Thin section consistent with D1, D2, D3 – groundmass of plagioclase lathes with pyroxene and biotite clasts, dotted with magnetite

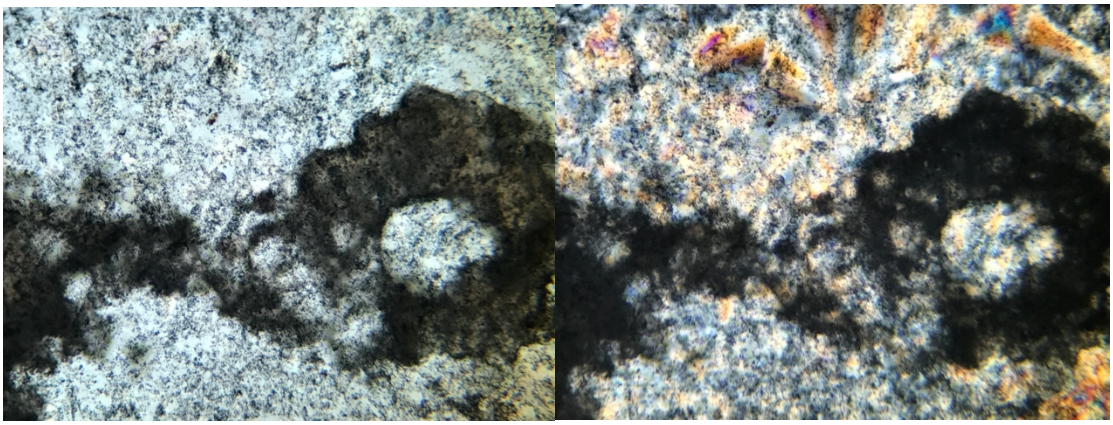
microcubes. Some pyroxene crystals appear structurally different than D1-D3; disintegration, dehydration of weathered ‘daughter’ mineral (amphibole)?



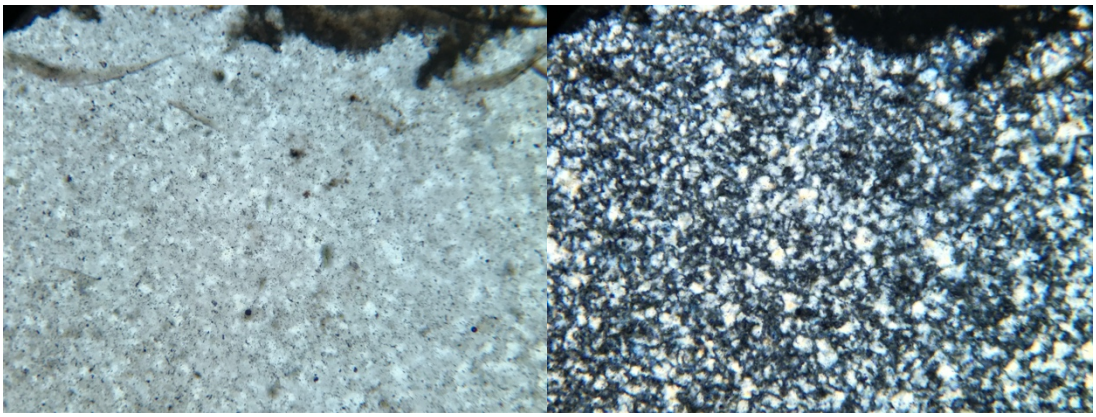
D5. 1000°C, 3 hours. No visible color or structural change. Thin section shows dramatic loss of material; subsequent XRD analysis indicates a loss of ‘pyroxenes’ (more likely weathered daughter material such as amphibole or mica). In thin section, groundmass remains flow banded plagioclase lathes. Some pyroxenes and biotites still present, as are magnetite microcubes. Loss of material appears as vesicules, circular to sub-rounded, and regular throughout. This voiding (vesiculation) effect is barely visible on the thin section slide.

E. Chalcedony

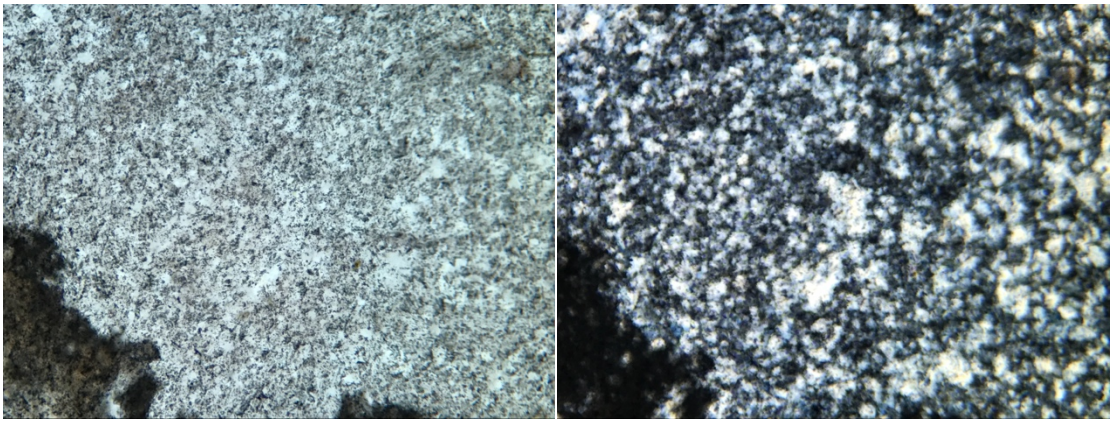
Field identification as **East African Chalcedony**. Translucent amber and white banded fine-grained rock exhibiting conchoidal fracture. Glassy luster, brittle. Hardness of 6.5-7.



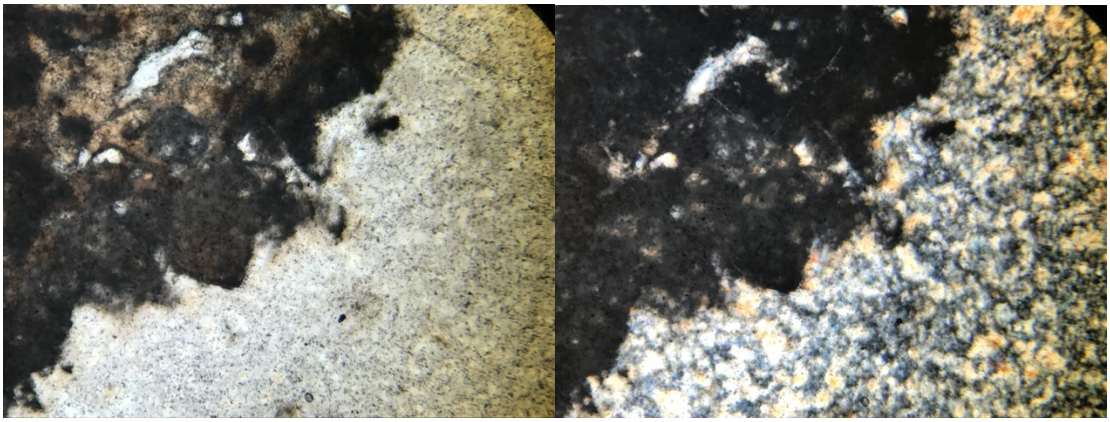
E1. Unheated thin section shows irregular microcrystalline quartz grains, with occasional feathery, botyroidal habit displaying undulose extinction.



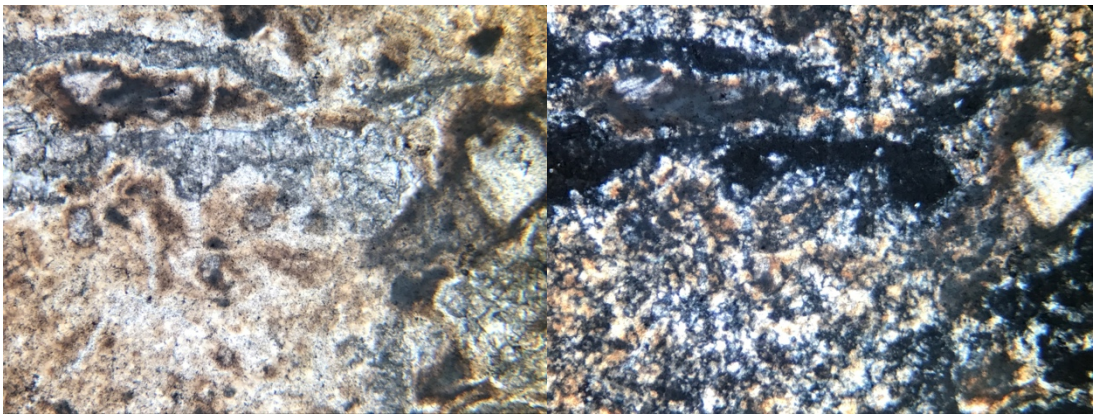
E2. 250°C, 3 hours. No visible or apparent structural change from E1. Thin section consistent with E1 – irregular medium salt and pepper microcrystalline quartz grains, interspersed with larger feathery quartz cyrstals.



E3. 500°C, 3 hours. Pinkish-white, translucent shows reddening; dull, friable. Thin section shows microcrystalline quartz salt and pepper effect more homogenous than E1, E2. Brown opaque inclusions darker than in E1, E2.



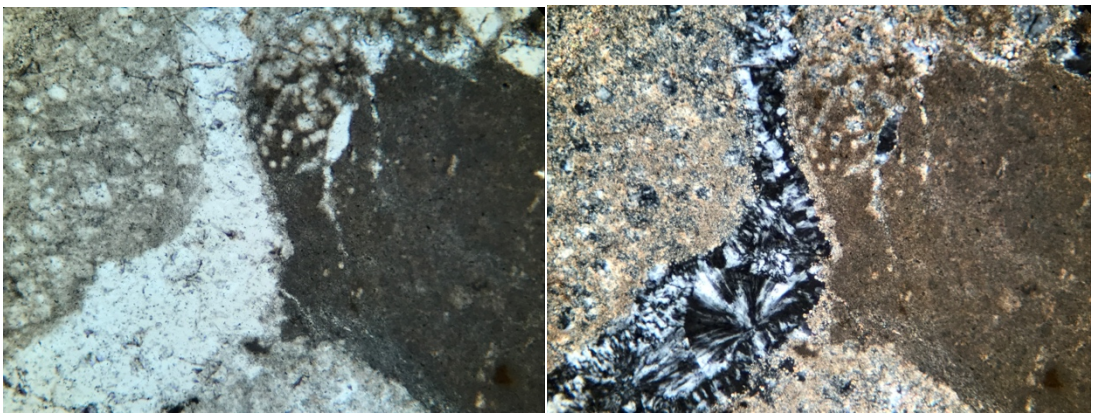
E4. 750°C, 3 hours. Greyish-white throughout; amber translucence gone. Some red speckling and black inclusions apparent. Dull, friable. Thin section displays less opaque inclusions and increased percentage of homogenous salt and pepper microcrystalline quartz.



E5.1000°C, 3 hours. Chalky white throughout with red-brown speckling and small black vein-like inclusions. Flat, friable and crumbling. Thin section shows voids, recrystallization of homogenous salt and pepper microcrystalline quartz, interspersed with brown inclusions.

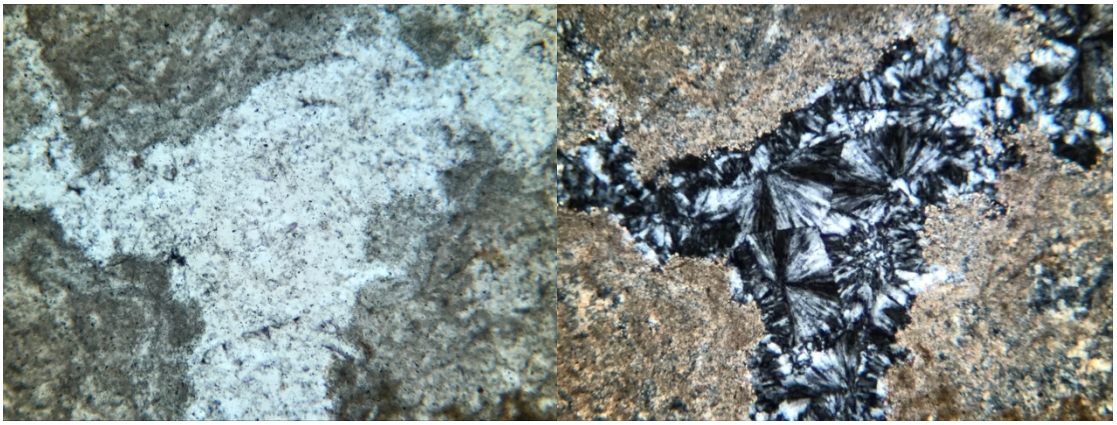
F. Chert

Field identification as **East African Chert**. Pinkish-beige fine-grained rock with small black spot inclusions, exhibiting conchoidal fracture. Waxy, dull luster, brittle. Hardness of 6-7.

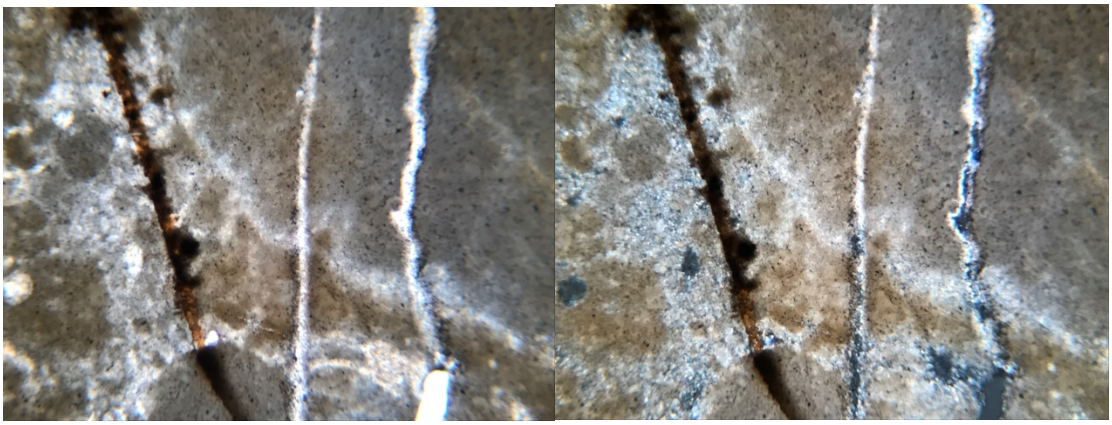


F1. Unheated thin section very fine-grained microcrystalline quartz salt and pepper groundmass, colorless to grey/beige in PPL. Intergrown with larger quartz veins of fibrous habit showing strong undulose extinction. Dark veins and clasts of small opaque inclusions, highly reflective under PRL – magnetite? Pyrite? Hematite?

F1. PPL on left, reflected light on right. The bright spots indicate pyrite or hematite inclusions.

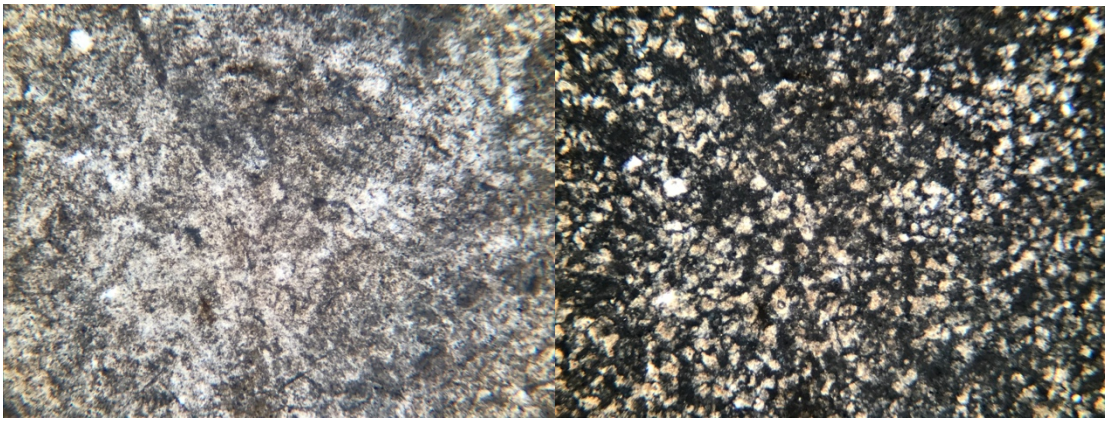


F2. 250°C, 3 hours. Dark grey throughout with pale pinkish-white banding; few small black spot inclusions. Dull, no apparent structural change. Thin section consistent with F1 – very fine-grained microcrystalline quartz displaying velvety, salt and pepper appearance intergrown with larger quartz showing fibrous habit with strong undulose extinction. Dark veins and clasts tending towards opaque browns, and small opaque black inclusions highly reflective in PRL.

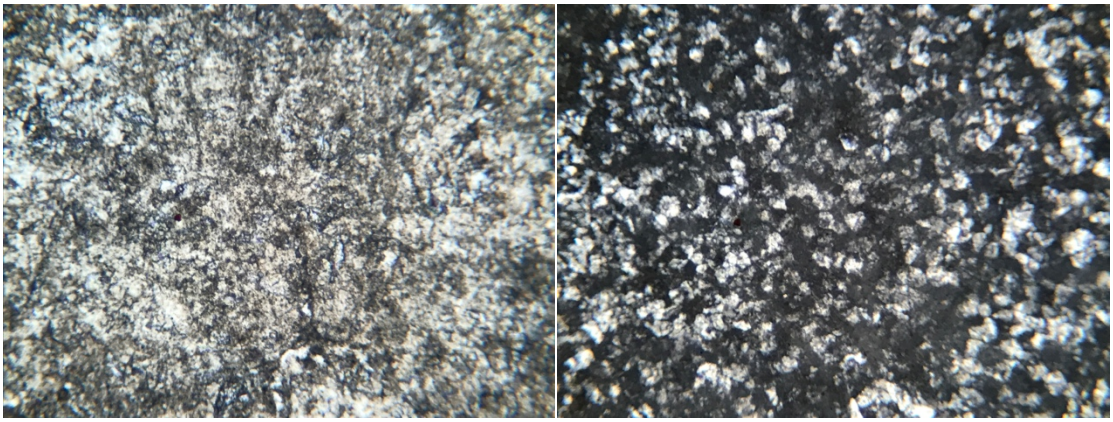


F3. 500°C, 3 hours. Very dark grey/brown with dark pink banding; flat luster, friable. Thin section shows fine-grained microcrystalline quartz in salt and pepper appearance, with

intergrowth of larger quartz crystals displaying fibrous habit with strong undulose extinction. Opaque inclusions and masses display darker brown oxidation than F1, F2.



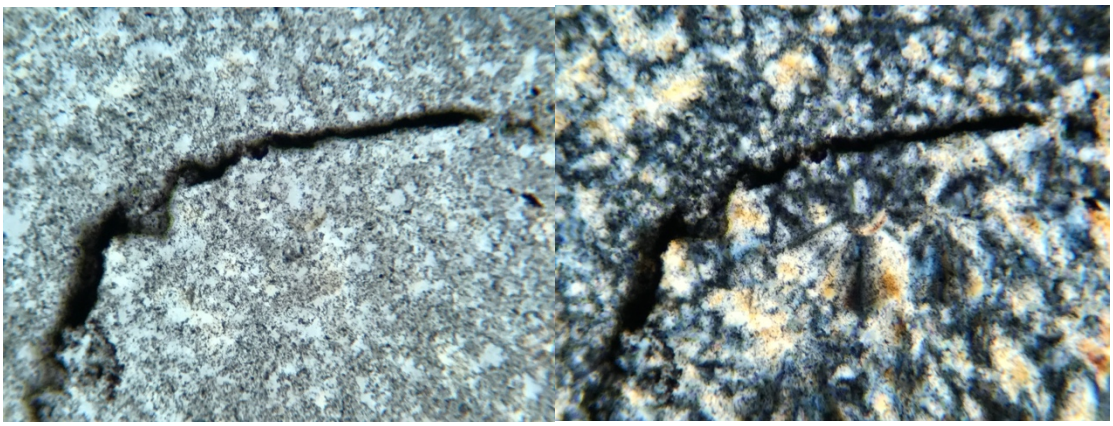
F4. 750°C, 3 hours. Whitish pink and black; flat luster, friable and crumbling. Thin section indicates fracturing of fine-grained microcrystalline quartz and appearance of voids (cracks?). Larger quartz fibrous crystals darkened to brownish color. Opaque inclusions significantly darker brown than F1, F2.



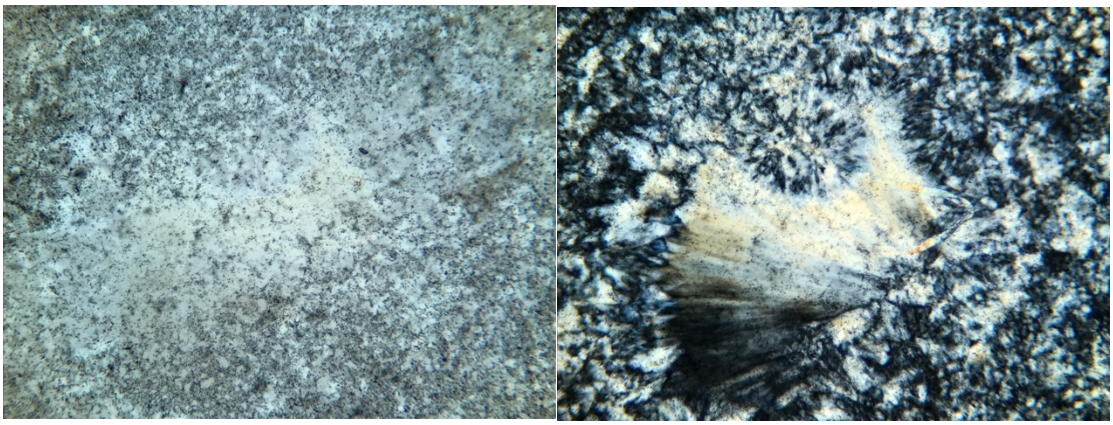
F5. 1000°C, 3 hours. White throughout with tiny black inclusions; flat luster, friable and crumbling. Thin section shows microcrystalline quartz fractured and disorganized in greys and browns; larger quartz fibrous crystals dark brown, still showing undulose extinction. Small black inclusions persist.

G. Chalcedony

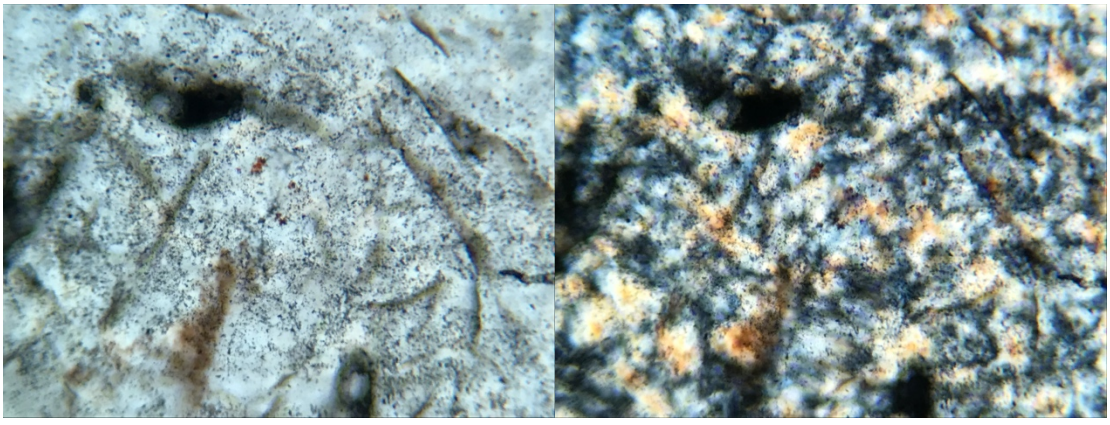
Field identification as **East African Chalcedony**. Translucent grey very fine-grained rock with black speckled inclusions exhibiting conchoidal fracture. Waxy, glassy luster; brittle. Hardness of 6.5-7.



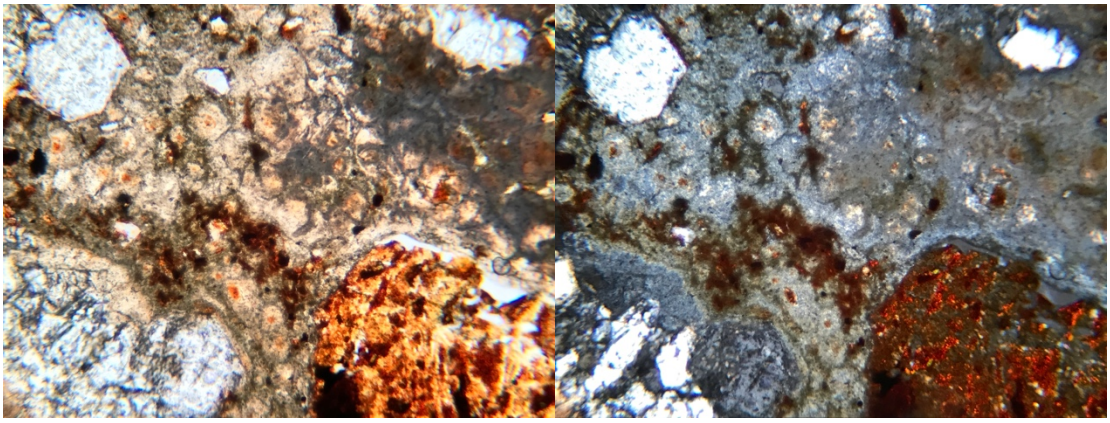
G1. Unheated thin section displays groundmass of salt and pepper, velvety, microcrystalline quartz interspersed with larger quartz crystals showing fibrous, botyroidal habit and strong undulatory extinction. Quartz is colorless in PPL, and first order yellow, grey in XPL. Small framboidal clusters of opaque mineral (hematite? Pyrite?) highly reflective (yellow) under PRL.



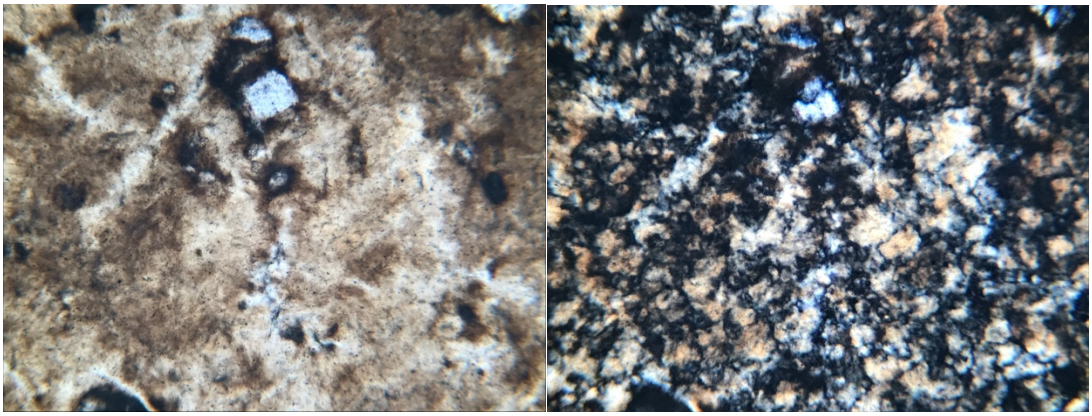
G2. 250°C, 3 hours. Consistent with G1 – translucent grey with black or brown speckled inclusions. Waxy, glassy; no structural change. Thin section consistent with unheated G1 – very fine-grained groundmass of salt and pepper microcrystalline quartz interspersed with larger growths of fibrous quartz. Small inclusions of opaque (pyrite?) highly reflective (yellow) under PRL.



G3. 500°C, 3 hours. Consistent with G1 – translucent grey with black inclusions, showing some reddening speckles (oxidation) and white opaque areas. Waxy, glassy; no apparent structural change. Thin section shows salt and pepper microcrystalline quartz interspersed with larger quartz fibrous in-growths. Some microfracturing of quartz evident. Framboidal cluster inclusions of (pyrite?) opaque material are highly reflective (yellow) under PRL.



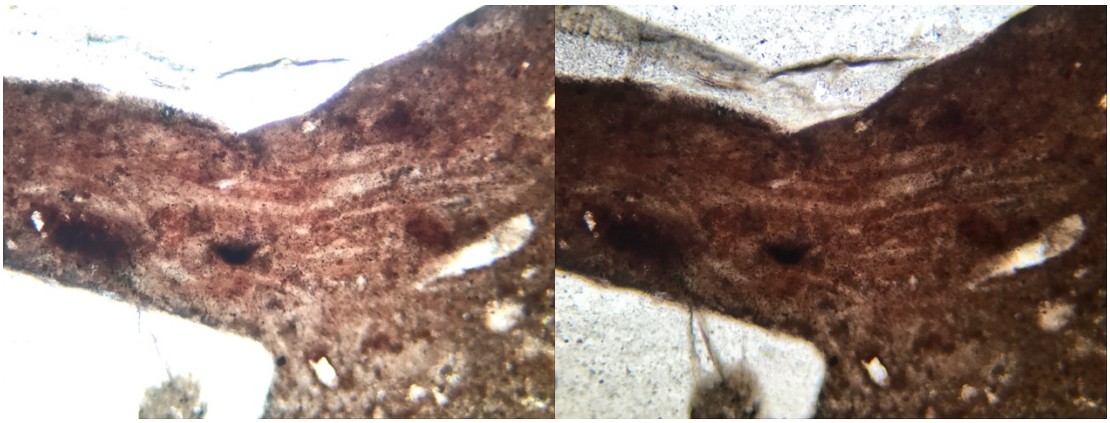
G4. 750°C, 3 hours. White opaque with grey banding and black inclusions. Flat luster; chalky, friable, crumbling. Thin section PPL show dark discoloration of salt and pepper microcrystalline quartz. Groundmass is red-brown in XPL, larger quartz crystals in fibrous habit also discolored to beige, brown and red. Small inclusions and framboidal clusters of opaque (pyrite?) are dark brown, with highly reflective small crystals in PRL.



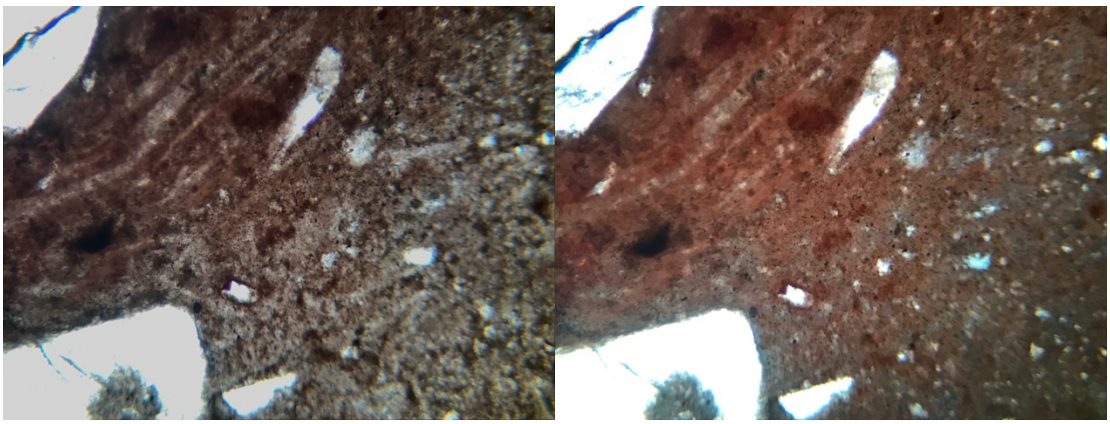
G5. 1000°C, 3 hours. White opaque throughout, showing cracks and visible fracturing; chalky, friable, crumbling. Thin section suggests groundmass of microcrystalline quartz has vitrified and recrystallized; light and dark brown in color, aggregated grains are larger compared to G1, G2. Microfracturing is evident. Opaque framboidal clusters of (pyrite? Hematite?) dark brown-red, highly reflective in PRL.

J. Red Ignimbrite

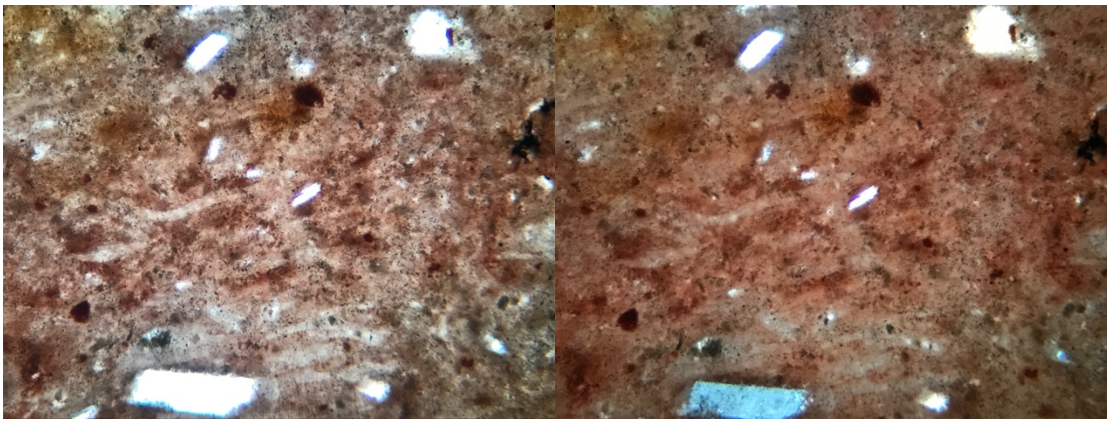
Field identification as **East African Red/Pink Ignimbrite**. Reddish-pink fine-grained rock exhibiting conchoidal fracture. Dull luster, lightly mottled with yellow and dark green crystals, occasionally showing sparkle.



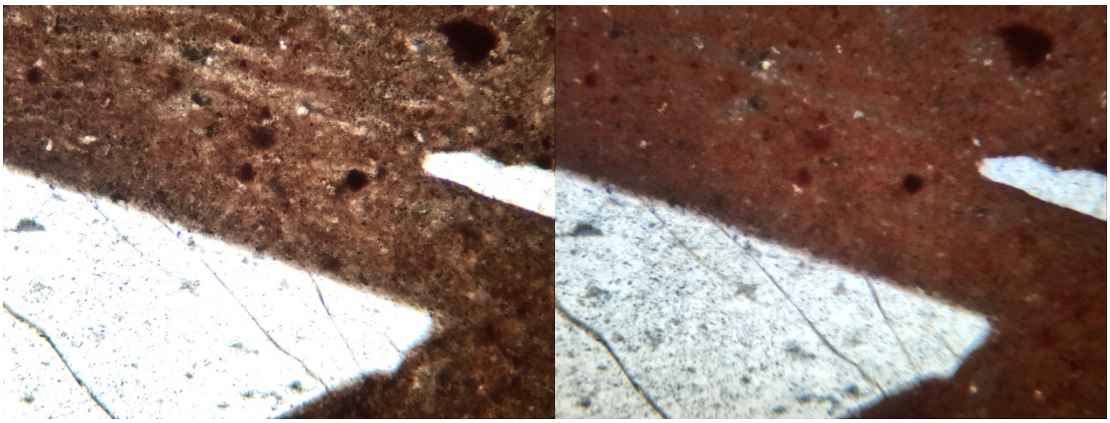
J1. Unheated thin section shows reddish brown flow banded eutaxitic lapilli tuff in a groundmass of welded fine-grained glass shard, intersperse with flattened pumice clasts and inclusions of biotite, feldspar and quartz phenocrysts. Red color possibly indicating presence of hematite. Feldspar crystals are tabular, often showing Carlsbad twinning or zoning, are colorless in PPL with birefringence at 0.002-0.006 1st order grey or white, yellowish-white and non-pleochroic. Biotite sometimes hexagonal in cross-section, showing one cleavage, moderate to high relief, strong pleochroism, birds-eye extinction and 3rd to 4th order birefringence of brown, red-brown and brown-green colors. Quartz grains are colorless, show no pleochroism, low positive relief with low order birefringence white tinged with yellow (0.009), no cleavage, no twinning but does show undulatory extinction. Alkali feldspar crysts appear colorless in plain polarized light, showing no pleochroism, low 1st order birefringence in grey color and exhibiting simple twinning with 90° cleavage.



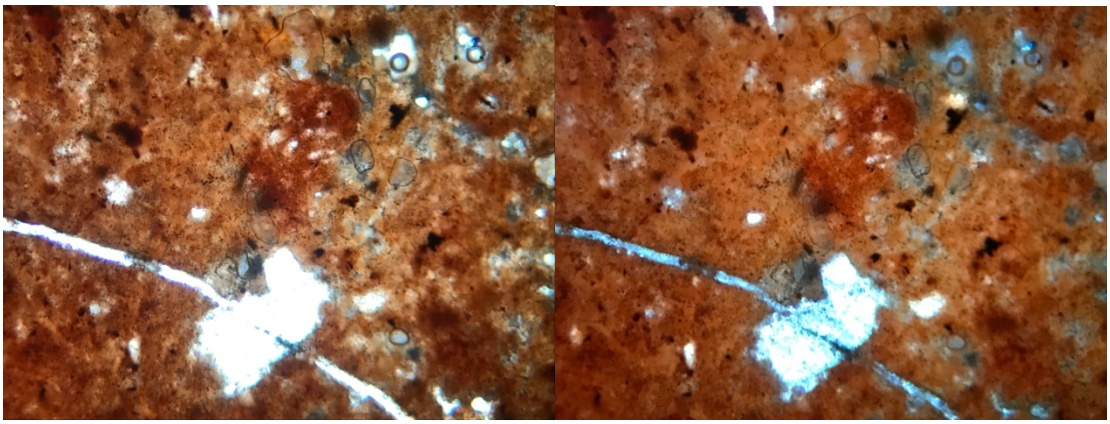
J2. 250°C, 3 hours. No visible change in color or structure. Thin section resembles J1 with no apparent modification. Groundmass of red-brown lapilli tuff exhibiting flow banding habit with included phenocrysts of sanidine, quartz and biotite.



J3. 500°C, 3 hours. Dark red-brown in color, structure somewhat friable. Thin section shows consistent with J1 and J2. Groundmass of red-brown lapilli tuff with flow banding and inclusions of sanidine, biotite and quartz crysts.



J4. 750°C, 3 hours. Dull grey-red in appearance, friable, crumbling. Thin section appearance shows reduced flow banding in welded glass. Groundmass exhibiting red-brown color with less organization. Phenocrysts of biotite, feldspar and quartz persist.

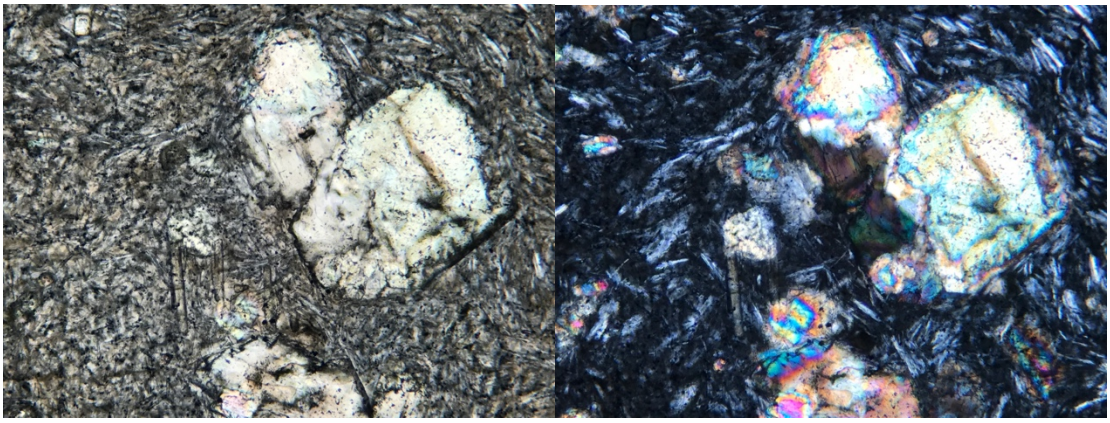


J5. 1000°C, 3 hours. Dull grey and white in appearance, friable, crumbling. Thin section shows disorganization of lapilli tuff and significant microcracking in groundmass. Groundmass is

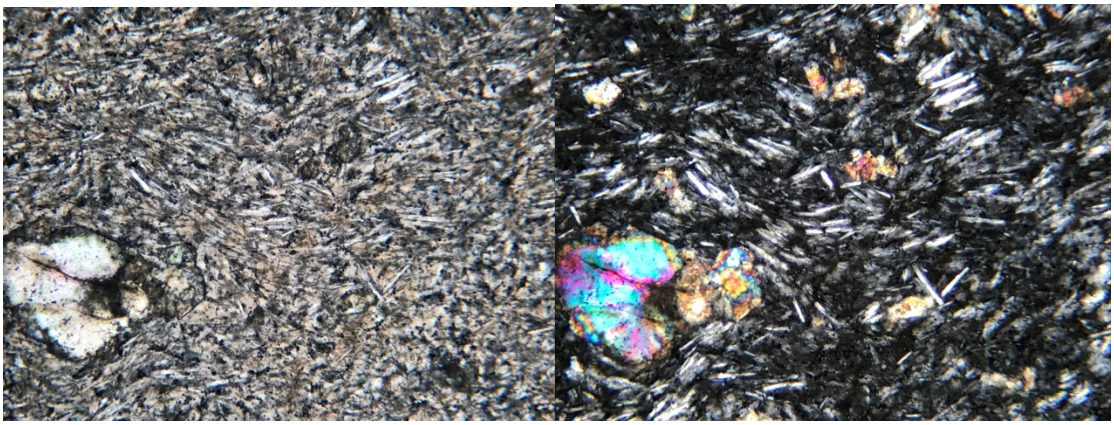
orange interspersed with yellow. Voids are present (resin bubbles in irregular voids). Phenocrysts of biotite and feldspar persist.

L. East African (Basaltic) Andesite

Field identification as East African Basalt. Laboratory identification as andesite. Fine grained black stone, conchoidal fracturing; harden of 6.5-7.

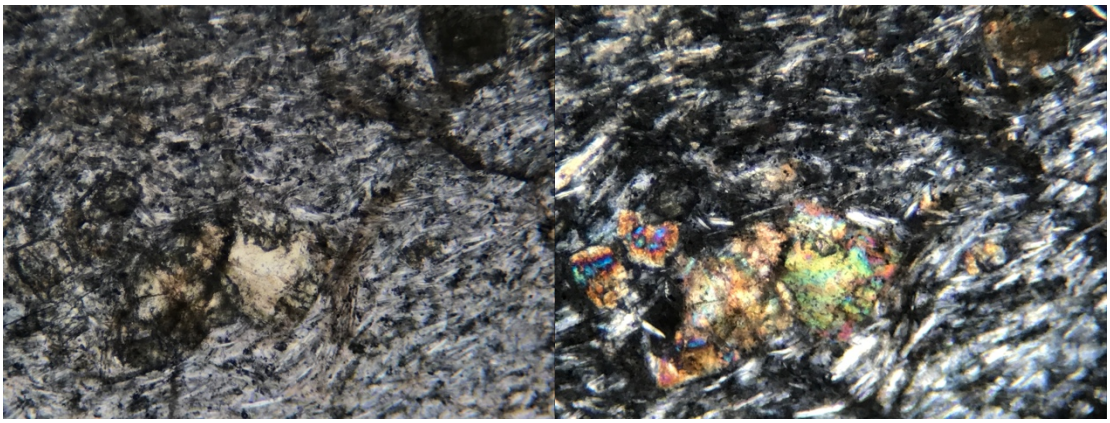


L1. Unheated thin section exhibits groundmass of foliated plagioclase lathes exhibiting twinning, interspersed with porphyritic phenocrysts of biotite and pyroxene.

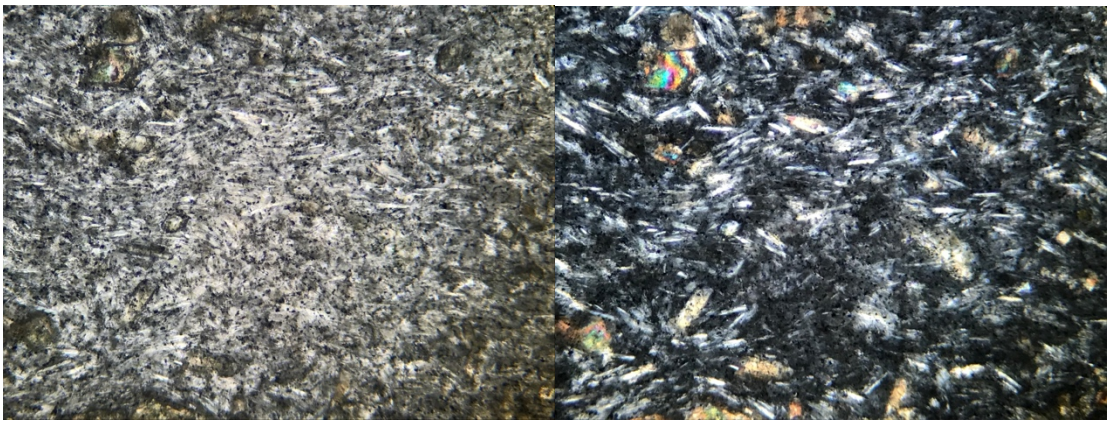


L2. 250°C, 3 hours. No visible change. Thin section consistent with L1 and shows no modifications. Groundmass of foliated plagioclase lathes interspersed with phenocrysts of biotite and pyroxene.

L3. 500°C, 3 hours. No visible change. Thin section consistent with L1, L2. Groundmass of foliated plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Some microcubes of magnetite apparent.

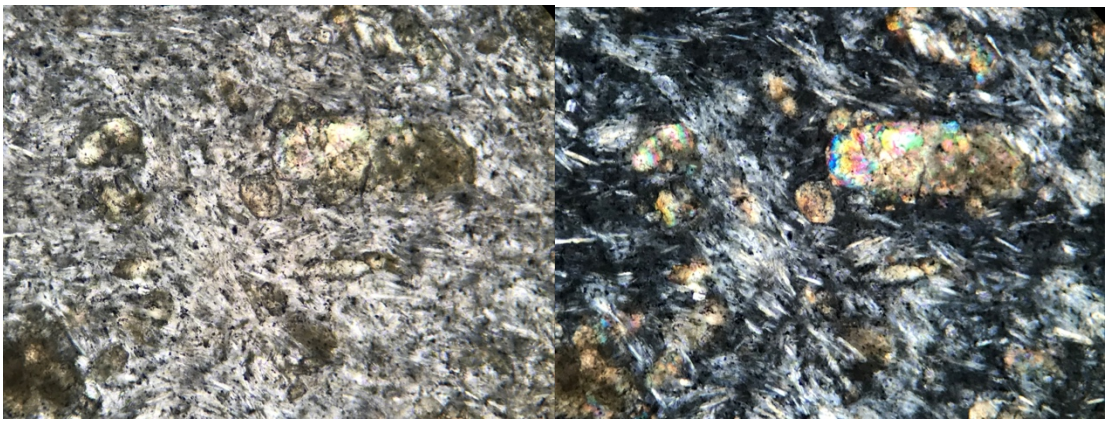


L4. 750°C, 3 hours. No visible change, no apparent texture or structural change. Thin section consistent with L1-L3. Groundmass of plagioclase lathes interspersed with phenocrysts of pyroxene and biotite.

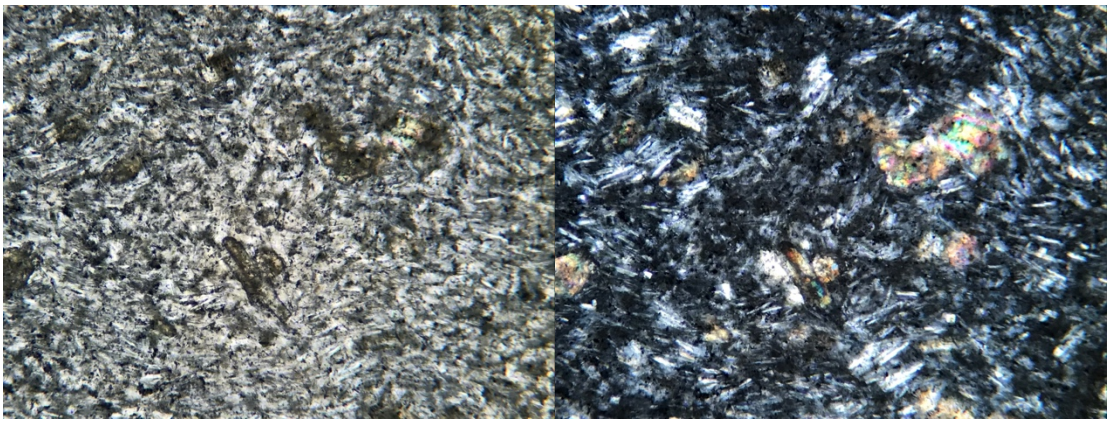


L5. 1000°C, 3 hours. No visible color, structural or textural changes. Thin section consistent with L1-L4. Groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Microcubic magnetite appearing as opaque black.

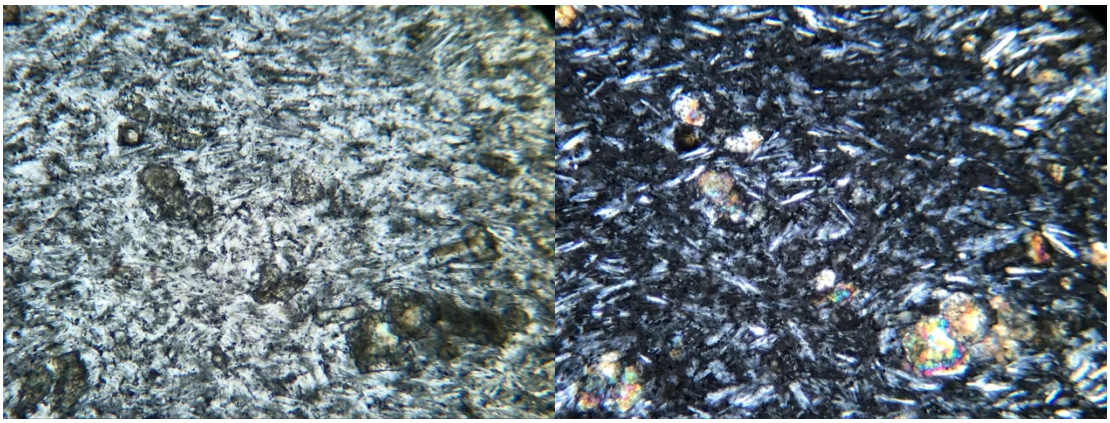
R. **East African Basalt** (Karari, Kenya). **Second phase experiments, muffle-furnace heatings.** This sample is from same parent material as sample D, above.



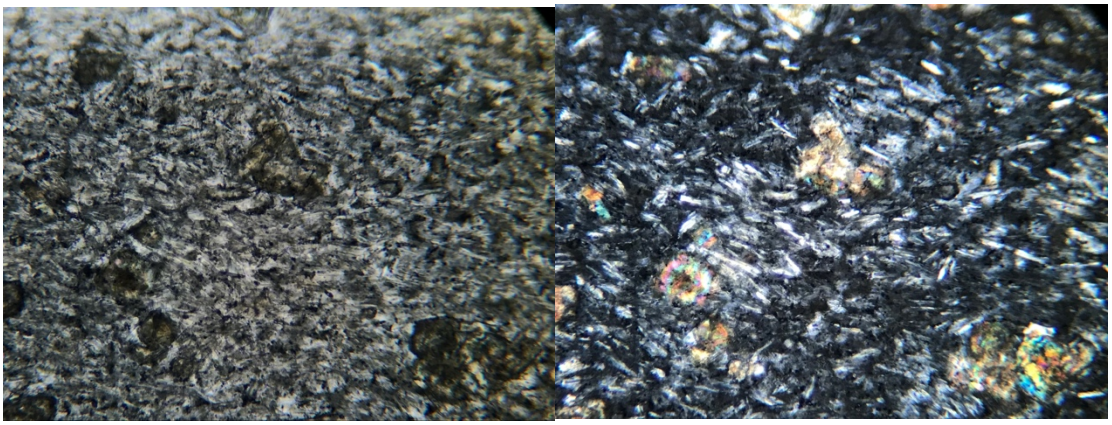
R1. 1000°C, 10 minutes. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 above. Closely resembles D1-D3. No evidence of voids.



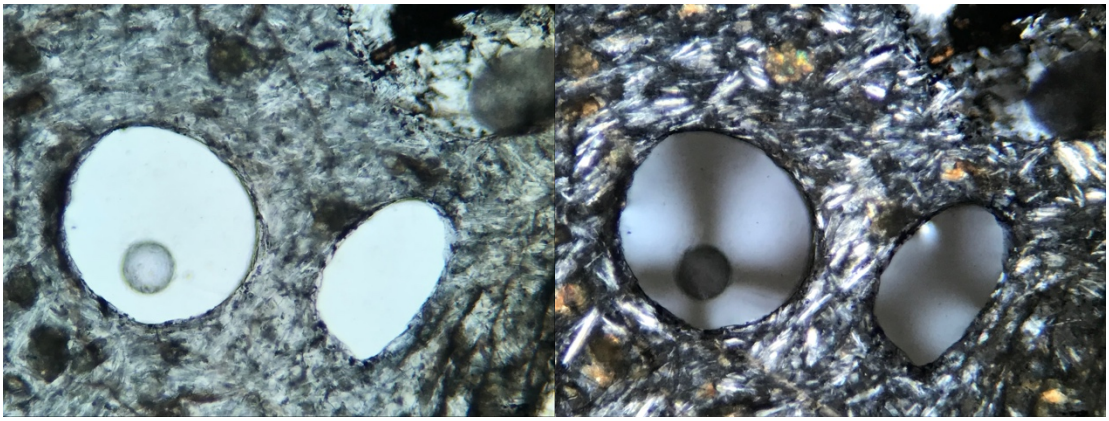
R2. 1000°C, 30 minutes. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 above. Closely resembles D1-D3. No evidence of voids.



R3. 1000°C, 1 hour. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 above. Closely resembles D1-D3. No evidence of voids.

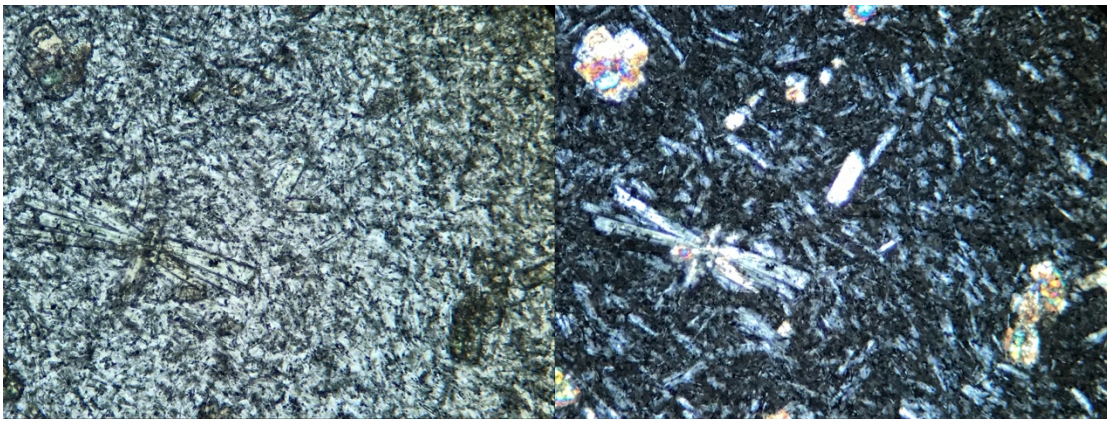


R4. 1000°C, 5 hours. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 above. Closely resembles D4. No clear evidence of voids.

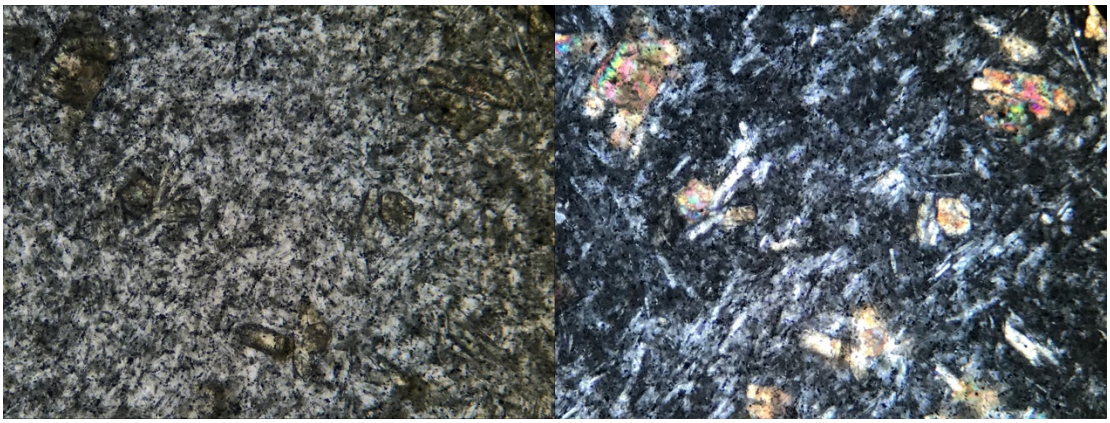


R5. 1000°C, 24 hours. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 above. Closely resembles D5. Heat-induced voids now clearly present.

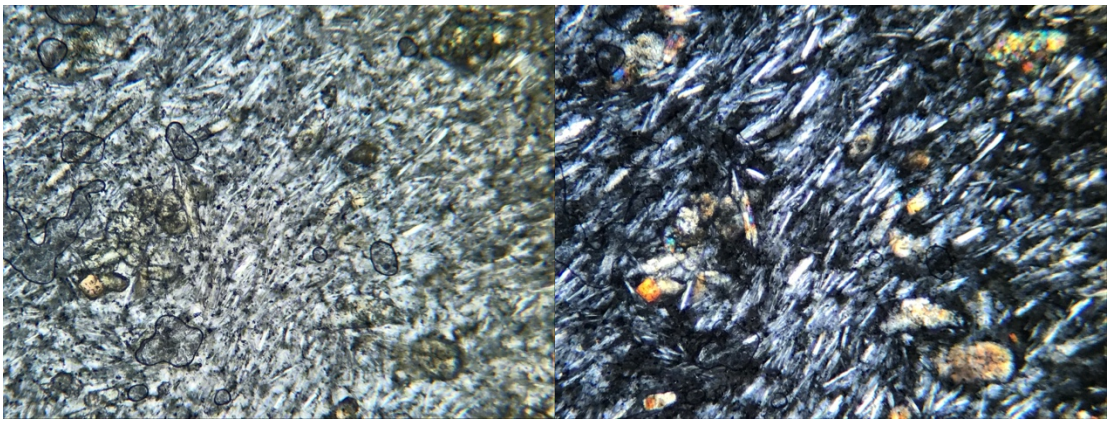
S. **East African Basalt** (Ileret, Kenya). **Second phase experiments, muffle-furnace heatings.** This sample is from same parent material as sample L, above.



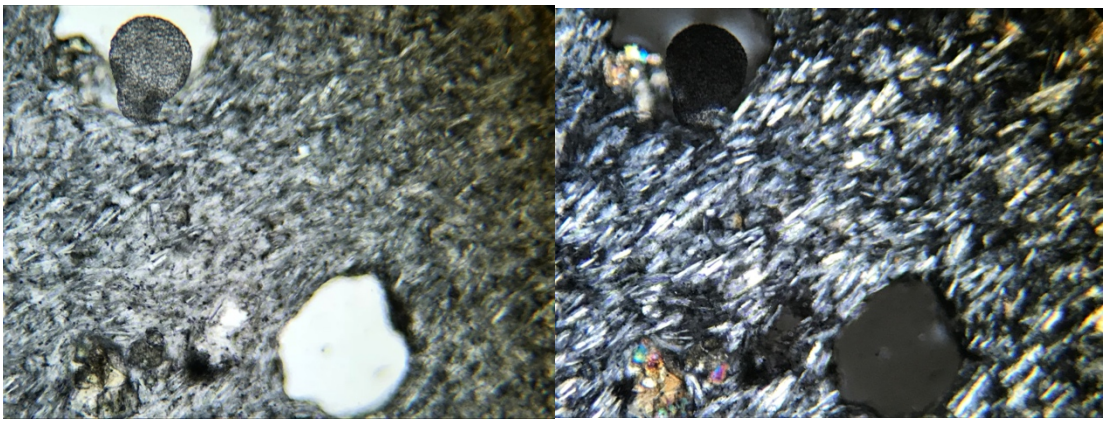
S1. 1000°C, 5 minutes. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 and L1-L5 above. Closely resembles L1-L3. No evidence of voids.



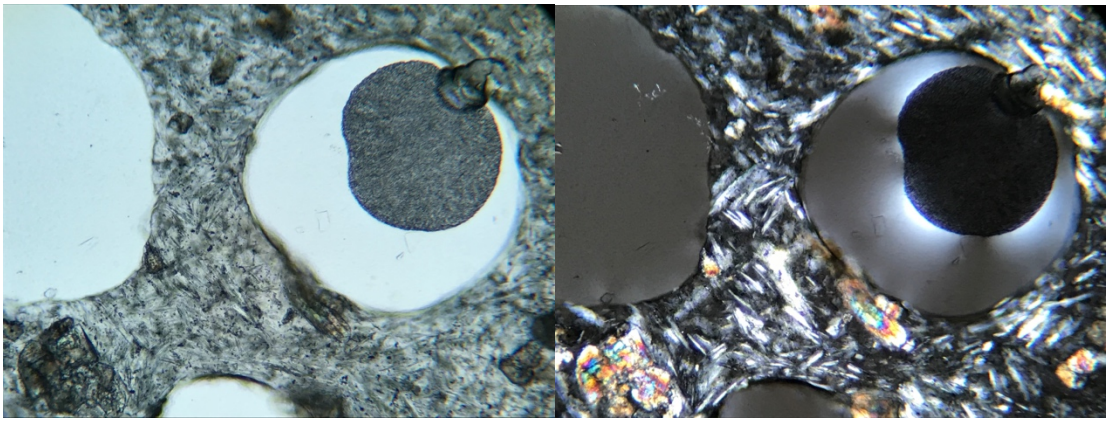
S2. 1000°C, 30 minutes. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 and L1-L5 above. Closely resembles L1-L3. No evidence of voids.



S3. 1000°C, 1 hour. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 and L1-L5 above. Closely resembles L1-L3. No evidence of voids.

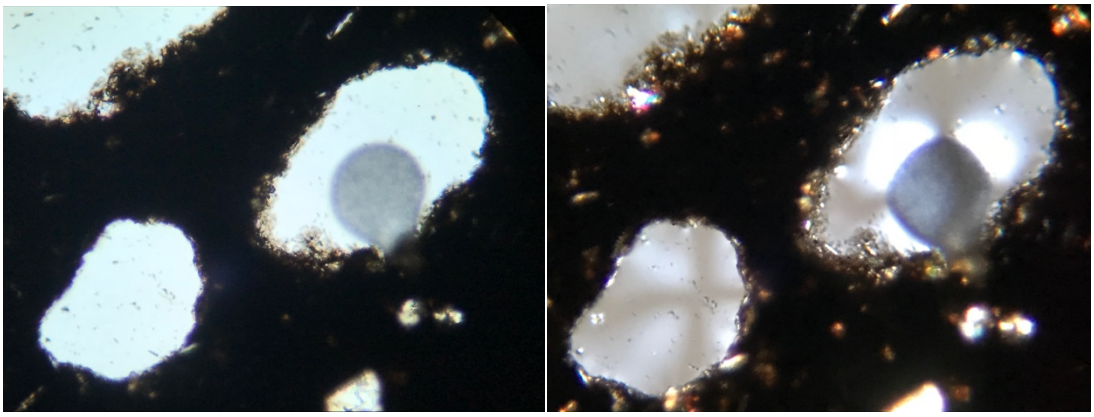


S4. 1000°C, 5 hours. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 and L1-L5 above. Closely resembles D5. Clear evidence of heat-induced voids present.

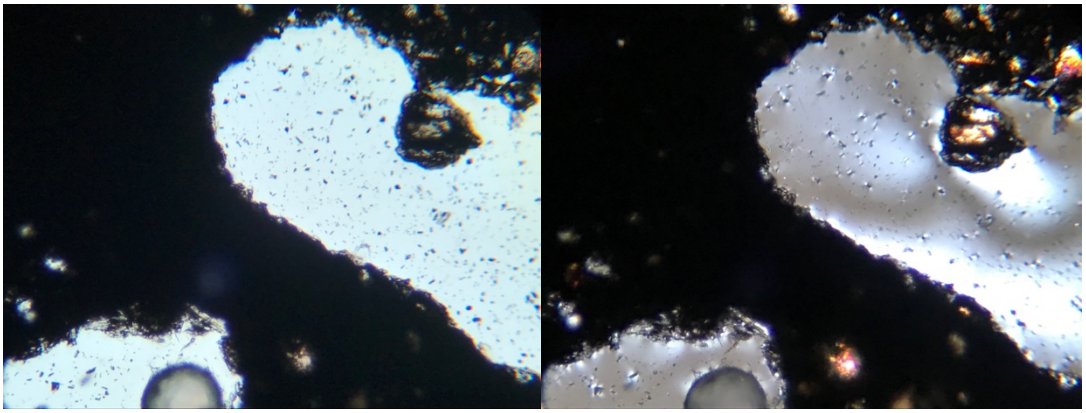


S5. 1000°C, 24 hours. Thin section shows fine grained groundmass of plagioclase lathes interspersed with phenocrysts of biotite and pyroxene. Compare to D1-D5 and L1-L5 above. Closely resembles D5. Clear evidence of heat-induced voids present.

U. **North American Vesicular Basalt**.
Fine grained black-grey stone with macroscopically visible vesicles.



U1. Vesicular Basalt (unheated). PPL on left, XPL on right. Flow banded plagioclase lathes interspersed with phenocrysts of pyroxene. Vesicles show translucent rough edging, irregular, often with phenocrysts of pyroxene embedded.



U2. Vesicular Basalt. 1000°C, 3 hours. PPL on left, XPL on right. No significant change in appearance from unheated sample.