Later Stone Age toolstone acquisition in the Central Rift Valley of Kenya: Portable XRF of Eburran obsidian artifacts from Leakey’s excavations at Gamble’s Cave II

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\textbf{A R T I C L E   I N F O}

\textbf{Keywords:}
Obsidian sourcing
Raw material transfer
Naivasha-Nakuru Basin
African Humid Period
Hunter-gatherer mobility
Human-environment interactions

\textbf{A B S T R A C T}

The complexities of Later Stone Age environmental and behavioral variability in East Africa remain poorly defined, and toolstone sourcing is essential to understand the scale of the social and natural landscapes encountered by earlier human populations. The Naivasha-Nakuru Basin in Kenya’s Rift Valley is a region that is not only highly sensitive to climatic changes but also one of the world’s most obsidian-rich landscapes. We used portable X-ray fluorescence (pXRF) analyses of obsidian artifacts and geological specimens to understand patterns of toolstone acquisition and consumption reflected in the early/middle Holocene strata (Phases 3–4 of the Eburran industry) at Gamble’s Cave II. Our analyses represent the first geochronological source identifications of obsidian artifacts from the Eburran industry and indicate the persistent selection over time for high-quality obsidian from Mt. Eburru, ∼20 km distant, despite changes in site occupation intensity that apparently correlate with changes in the local environment. This result may indicate resilience of Eburran foraging strategies during environmental shifts and, potentially, a cultural preference for a specific lithic material that overcame its accessibility changes. Testing such hypotheses requires a more extensive program of obsidian artifact sourcing. Our findings demonstrate the great potential for sourcing studies in the Rift Valley as well as underscore the amount of work that remains to be done.

\textbf{1. Introduction}

The complex dynamics of Holocene interglacial environmental and behavioral variability in East Africa remain poorly defined. Significant and often abrupt environmental changes include the return to near-glacial conditions during the Younger Dryas event (∼12.9–11.7 ka), followed by the African Humid Period (AHP, ∼11–6 ka), and a return to more arid conditions (∼6–4 ka; e.g., Gasse, 2000; Tierney and deMenocal, 2013). Changes during the AHP are particularly striking, including the “Green Sahara” phase of northern Africa, with a number of East African lakes expanding in size and depth, coincident with the expansion of more forested ectones (Butzer, 1972; Hamilton, 1982; Bergner et al., 2009; Trauth et al., 2010). Archaeologically, a number of regionally distinct artifact traditions are recognized, including the Kanyore fisher-foragers of the Lake Victoria basin (Dale and Ashley, 2010), fisher-forager communities who produced the “dotted-wavy line” pottery and barbed harpoons found throughout parts of the Sahara and the Sahel as far south as Lake Turkana (Wright et al., 2015; cf. Sutton, 1974; Holl, 2005), and the Eburran industry produced by foragers in the Central Kenyan Rift Valley (e.g., Ambrose, 1984; Wilshaw, 2016). Cattle, sheep, and goat spread southward from northern to eastern Africa by ∼7 ka, resulting in a complex cultural and economic mosaic that was in place by 3 ka (di Lernia, 2013; Kusimba, 2003; Lane, 2013; Skoglund et al., 2017).

A number of unanswered questions remain about the archaeology of this timeframe. For example, do distinctive regional behavioral entities (e.g., archaeological industries like the Eburran) form because of adaptations to specific habitats, as a result of isolation from neighboring groups, or as a deliberate expression of what Wiessner (1983) referred to as emblemic style? Does the spread of pastoralism reflect the demic diffusion of groups along an expanding frontier or a series of local adaptations as stock is transferred along existing social networks among foraging groups (cf. Lane, 2004; Prendergast, 2010; Skoglund et al., 2017)? Answering these questions ultimately requires

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https://doi.org/10.1016/j.jasrep.2018.01.042
Received 24 July 2017; Received in revised form 23 January 2018; Accepted 28 January 2018
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establishing the nature and strength of inter-group connections, which is not straightforward, particularly using archaeological data. Fortunately, artifacts made of obsidian are common at many AHP sites in East Africa, particularly in Kenya, and identifying the geological sources of these artifacts can enhance our understanding of the extent to which different regions – and, in turn, the populations within them – were connected in the past.

There are > 80 geochemically distinct obsidian sources along an 800-km stretch of Kenya between Lake Turkana on the Ethiopian border and Lake Natron on the Tanzanian border (Brown et al., 2013). Of these, roughly two-thirds lie within Kenya's Naivasha-Nakuru Basin and its surroundings, and there is now a fairly robust geochemical database for source outcrops as well as Pleistocene-Holocene artifacts made by foragers and pastoralists from sites in Kenya and Tanzania (e.g., Merrick and Brown, 1984a, 1984b; Merrick et al., 1988, 1994; Mehlman, 1989; Coleman et al., 2008, 2009; Nash et al., 2011; Ndiema et al., 2011; Ambrose et al., 2012a, 2012b; Ferguson, 2012; Prendergast et al., 2013; Faith et al., 2015; Blegen, 2017; Blegen et al., 2017; Frahm et al., 2017). From the extant data, a few generalizations can be made. First, foragers and pastoralists in the Lake Turkana basin appear to have used locally available obsidian sources, which means there is no strong evidence in these data to support cultural connections between the Turkana region and the Naivasha-Nakuru Basin. Second, pastoralist groups relied extensively on sources within the Naivasha-Nakuru Basin, transporting large quantities of obsidian across long distances (often ≥100 km), particularly to the south. Third, there has been persistent movement of obsidian from the Naivasha-Nakuru Basin into the Lake Victoria basin. Connections between these regions date to at least the Late Pleistocene (Faith et al., 2015; Blegen et al., 2017) and persist throughout the Holocene, including portions of the AHP (Merrick and Brown, 1984a, 1984b; Frahm et al., 2017) that overlap in time with Kansyore sites in the Lake Victoria basin and assemblages attributed to the Eburran industry in the Naivasha-Nakuru Basin.

Apparent connections between foragers in the Lake Victoria basin (e.g., Kansyore groups) and groups in the Naivasha-Nakuru Basin (e.g., Eburran producers) are based entirely on obsidian sourcing data from sites in the Lake Victoria basin, that is, from sites ~200 km from the sources. As yet, there are no published geochemical data on obsidian artifacts found at Eburran industry sites. Such data can serve as a means to better understand the extent of connections between these two areas. To initiate this, we focus on collections from Gamble's Cave II (GC2; Kenya), the type-site for Phases 3, 4, and 5 of the Eburran industry. In particular, we focus on a collection of GC2 obsidian artifacts from L.S.B. Leakey's 1920s excavations housed at Harvard University's Peabody Museum of Archaeology and Ethnology. This subsample of the GC2 assemblage reflects what Leakey (1931) termed the “fourth occupation level” of GC2. He initially subdivided it into the Kenyan Aurignacian Phases a and b, which were subsequently designated as the type deposits for Phases 3 and 4 of the Eburran industry (see Ambrose et al., 1980; Ambrose, 1984; Wilshaw, 2016).

Using state-of-the-art portable X-ray fluorescence analysis (pXRF), we chemically identified the geological sources of 239 GC2 obsidian artifacts. pXRF instruments offer archaeologists several advantages over techniques traditionally used for obsidian sourcing. First, pXRF is nondestructive, meaning that artifacts do not need to be polished, powdered, dissolved, or discarded. Second, it can be conducted at a museum, in a field house, or even at an archaeological site. Third, it can be rapid, often needing just a minute or two to measure dozens of elements. The first two advantages were paramount in this study. Recent studies demonstrate that newer pXRF instruments have technical advances (e.g., large-area Si drift detectors with high spectral resolution, adaptive signal-processing electronics) that enable excellent accuracy, reproducibility, and sensitivity (e.g., Frahm, 2014; Milici, 2014; Frahm and Feinberg, 2015; Newlander et al., 2015; Le Bourdonnec et al., 2015; Campbell and Healey, 2016; Bonsall et al., 2017; Orange et al., 2017; cf. older instruments in Potts and West, 2008; Drake et al., 2009; and Liritzis and Zacharias, 2011). In this study, our pXRF measurements were directly calibrated and compared to the published data of Brown et al. (2013) in order to determine the artifacts’ origins. We have previously documented that the XRF database of Brown et al. (2013) and our pXRF measurements are directly compatible (Frahm et al., 2017).

Our results for the Eburran Phases 3 and 4 at GC2 suggest that the site’s occupation history or local environment had no discernable effect – at least in this sample – on the variety or range of obsidian sources used for tool manufacture. Previously unpublished data for the site’s use indicate a higher occupation intensity during the more humid Eburran Phase 3, when the lake’s shoreline was likely closer at GC2 than at present. As the lakeshore retreated and, with it, the site’s position at an ecotone important to Eburran groups, the occupation intensity at GC2 decreased, as indicated by the lower frequency of retouched tools and artifact discard rates in the later deposits. In both phases, the closest source – Mt. Eburru at ~20 km distant – was consistently exploited to meet the demands for lithic material. This implies that demand for this toolstone outweighed ecologically linked changes in its accessibility to GC2 occupants. This result might also indicate the resilience of Eburran foraging strategies during the transition from an earlier, more humid interval and a later, drier one. Speculatively, these GC2 data might also mark the beginning of the widespread use of Mt. Eburru obsidian by foragers across Kenya and Tanzania. Testing such hypotheses requires a more extensive program of obsidian sourcing in the region, and our findings not only reveal the potential for such analyses but also underscore the amount of work that remains to be done.

2. Background

The GC2 rockshelter (0.55525° S, 36.08936° E, 1934 m) is an overhang cut into an interface between Quaternary lacustrine sediments and Pleistocene pyroclastics, where it formed during an early Holocene highstand of Lake Nakuru (Figs. 1–2; Washbourn-Kamau, 1971). Leakey excavated ~45 m² at GC2 to a depth of ~8.5 m in 1926–1929, and he recognized four “occupation levels” that include a number of early-to-late Holocene LSA obsidian blade-based lithic industries that span the transition to food production (i.e. pastoralism) and the local adoption of ceramics. These different occupation levels were only summarily described in his 1931 book The Stone Age Cultures of Kenya Colony. As Leakey (1971:iv) notes in a new introduction to the second printing of that book, “a very detailed report… on Gamble’s Cave II, was sent to press in Paris, just before the outbreak of World War II, but the whole report and all the illustrations and diagrams were mislaid or destroyed during the German Occupation.”

In 1964, Glynn Isaac and Ronald Clarke excavated a 1 × 2 m stratigraphic section at GC2 to collect material for radiocarbon dating. Ambrose (1984) provides a summary of lithic and faunal assemblages from the 1964 excavation. Materials from the Leakey and Isaac/Clarke excavations formed the basis for a major revision of the Holocene Later Stone Age (LSA) sequence in the Central Kenya Rift. The divisions are based on stratigraphy as well as changes in retouched tool type and, in particular, a size decline in blade and backed piece length over time. The early so-called “giant blade” Eburran Phases 1 and 2, which are not present at GC2, are dated to ~12 ka and 11.0–10.3 ka elsewhere in the Central Kenya Rift (Wilshaw, 2016). These are followed by Eburran Phase 3 and Phase 4, which are not very well dated at GC2. Reliable dates are restricted to a number of similarly aged radiocarbon determinations near the base of the Phase 3 deposits. Estimates from GC2 (based partially on inferred sedimentation rates) are generally consistent with those from other Eburran Phase 3 and Phase 4 assemblages, which suggest an age of ~8.5–8 ka for Phase 3 and ~7.8–6 ka for Phase 4 (Ambrose, 1984; Ambrose et al., 1980; Bower et al., 1977; Protsch, 1978; Wilshaw, 2016). These are, in turn, overlain by the ‘small blade’ Eburran Phase 5 (~4.5–1.8 ka) and by the Pastoral Neolithic Elmenteitan industries from ~3.2–1.4 ka (Goldstein and Munyiri, 2017).
GC2 is considered the type site for Eburran Phases 3 and 4 (as well as the Eburran Phase 5 and the Elmenteitan Neolithic industry; Ambrose, 1984), and Phases 3 and 4 are the focus of our research. The Eburran Phase 3 and 4 lithic technological system is geared towards the production of blades and bladelets from single or opposed platform cores made on angular spalls. These blades and bladelets were subsequently modified into several tool types, in particular a variety of backed pieces, with the larger blades segmented and transformed into smaller tools such as endscrapers and truncated/facetted pieces for the production of small flakes, bladelets, and burin spalls (Nelson, 1973;

Fig. 1. Map of the Central Rift Valley of Kenya, including the location of Gamble’s Cave II (GC2) and the obsidian sources identified at GC2 in the Eburran Phases 3 and 4 deposits. The light blue shaded areas correspond to Wilshaw’s (2012) lake level reconstructions ∼8 ka. Before that, ∼9.5 ka, the Nakuru-Elmenteita palaeo-lake reached all the way to – and formed – the GC2 rockshelter. See also the lake level reconstructions in Bergner et al. (2009) for their maximum extents. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Stratigraphic section from Leakey’s original excavations at GC2 (redrawn from Leakey, 1931: Figure 15; colors are arbitrary, selected for clarity).

Considerable research has focused on potential links among the Eburran-producing groups’ subsistence strategies, settlement locations, and shifting altitudes of savannah-bush-forest ecotones within this basin (e.g., Isaac, 1972; Ambrose et al., 1980; Ambrose, 1984, 1986, 2001; Ambrose and DeNiro, 1989; Ambrose and Sikes, 1991; Marean, 1992; Marean et al., 1994). Three main ecological zones exist at different altitude ranges in the Nakuru-Naivasha Basin: savannah (lowland), bush (mid-range) and montane forest (highland). Human settlement focus appears to track the position of the boundaries between them over time as they shifted in response to climatic changes (e.g., the bush and montane forest expands into lowland areas during wet times, the savannah expanded into higher altitudes in drier times).

The GC2 faunal assemblage appears to reflect at least some of these changes. Provenience data are poor for original faunal materials reported in Leakey (1931). Data reported from the Isaac and Clarke excavations consist of identifiable teeth only: 87 specimens from Phase 3 and 27 from Phase 4. Phases 3 and 4 are both dominated by small bovids (Ambrose, 1984; Marean, 1992). Ambrose (1984) interprets the Eburran Phase 3 deposits as indicative of forest or bush conditions, based on the presence of bushuck (Tragelaphus scriptus) and various duikers (Cephalophus sp.), consistent with evidence from Lake Nakuru and Lake Naivasha for more humid conditions when the lakes had expanded at this time and the lake margin was closer than at present (Richardson and Dussinger, 1986; Bergner et al., 2003, 2009). In contrast, the Phase 4 fauna are interpreted by Ambrose (1984) as indicative of a slightly more open bush and/or grassland landscape, suggested, in part, by higher proportions of reedbuck (Redunca cf. fulvorufa) in the Phase 4 deposits. This interpretation would be consistent with a general decline in lake size due to increased aridity that began ~6 ka or earlier (Richardson and Dussinger, 1986; Maitima, 1991), which, therefore, would have positioned GC2 farther from the lake margin in Phase 4 than during Phase 3.

3. Hypotheses

Because we are interested in the nature of diachronic changes within the Eburran, we use archaeological and obsidian source datasets to test three hypotheses about the occupation history of GC2.

Hypothesis 1. Occupation intensity was greater at GC2 during Eburran Phase 3. This hypothesis is based on paleoenvironmental data from GC2 and neighboring Eburran sites as well as theoretical models drawn from behavioral ecology. In general, we expect more wooded nearshore environments of Eburran Phase 3 at GC2 to provide a more dense and predictable resource base than the inferred drier and more open habitats during Eburran Phase 4, thereby supporting more intensive occupation at the site. A number of ethnographic and theoretical studies (e.g., Dyson-Hudson and Smith, 1978; Wiessner, 1982, 1983; Ambrose and Lorenz, 1990; Kelly, 2013; Marean, 2016) suggest that (1), with predictable and dense resources on the landscape, hunter-gatherers tend to have small ranges and make less frequent moves but (2), when resource productivity and predictability decrease, their home range sizes and mobility tend to rise.

Hypothesis 2. Occupation intensity was greater at GC2 during Eburran Phase 4. Based on data from the Isaac and Clarke excavations, Ambrose (1984) suggested, on the basis of patterning within the GC2 lithic and faunal data, more intensive occupation at GC2 occurred during Eburran Phase 4 relative to Phase 3. He noted there were considerably more retouched tools in Phase 4 relative to Phase 3, which he interpreted as increased occupation intensity. The Phase 4 retouched artifact assemblage showed reduced typological diversity relative to Phase 3, interpreted as the outcome of greater spatial segregation of activities tied to more intensive occupation (Ambrose, 1984). Finally, the greater number of complete and identifiable faunal elements (measured by teeth) in Eburran 3 levels were used to support this scenario, with the expectation of greater fragmentation (and thus fewer complete specimens) with increased occupation intensity during Eburran Phase 4.

Hypothesis 3. Greater occupation intensity correlates to increased reliance on local obsidian sources and greater diversity in the number of sources used. This hypothesis predicts an increased reliance on local obsidian sources, as tools, which are subject to more intensive and/or prolonged uses, are increasingly made or replaced at the site as needed. Similarly, the diversity of toolstone materials brought to the site should increase with occupation intensity as wider portions of the landscape are encountered during extended forays to procure toolstone or other resources (cf. Kühn, 1991; Surovell, 2009), as foraging range tends to increase with occupation duration (Hovers, 2009:158).

4. Materials and methods

Here we report how we tested these hypotheses, in particular the details of the sourced GC2 artifact assemblage, the pXRF instrument and analytical protocols, our specialized calibration for direct comparability with the published datasets of Brown et al. (2013), and our means of matching GC2 artifacts to their sources. We followed the procedures documented in Frahm et al. (2017), so readers interested in additional details regarding our protocols and their quality assessments are directed to that publication.

4.1. Archaeological assessments of mobility and occupation intensity

Ambrose’s (1984) estimates of occupation intensity and frequency are based on the number of retouched tools and on an inverse relationship between artifact and faunal densities at the site, with faunal density estimated entirely on the number of recovered teeth. The inferences were that more such artifacts reflect more use of a site and that greater, more intensive occupation results in increased faunal fragmentation and, in turn, fewer identifiable teeth for the Eburran 4 deposits. In terms of the lithic assemblage, research since Ambrose’s (1984) hypotheses were formulated have emphasized that the number of retouched tools alone is insufficient to infer either the frequency or intensity of site use. Specifically, Riel-Salvatore and Barton (2004; Barton and Riel-Salvatore, 2014) have shown that a superior measure is the frequency of retouched tools relative to the “artifact volumetric density,” that is, the total number of artifacts per excavated cubic meter for a particular assemblage or deposit. Because retouched tools are often components of the transported toolkit, assemblages made by highly mobile groups that stay at a given locality for only a short time tend to have relatively more retouched tools than sites occupied by groups that stay longer at a particular place on the landscape. In the latter case, with increased site occupation duration, the number of retouched tools becomes swamped by the more numerous flakes, flake fragments, and other debris associated with on-site tool production and upkeep.

Here we estimate occupation duration and intensity at GC2 by calculating average artifact discard rates, measured by dividing artifact totals by estimated time span, inferred from available radiometric and stratigraphic data. We also calculate the ratios of retouched tools to lithic artifact volumetric densities, as described by Riel-Salvatore and Barton (2004) and by Barton and Riel-Salvatore (2014). Age spans follow those provided by Ambrose (1984). Artifact abundances were calculated using retouched tool counts reported by Ambrose (1984) and previously unpublished data on the total number of artifacts recovered from the 1964 Isaac and Clarke excavation at GC2 (collected in 1978 by Charles Nelson and provided by him to us in 2017). Our obsidian sourcing data focus on an available sample excavated by Leakey. We use abundance data from the Isaac and Clarke excavations because their improved excavation and recording techniques reduce the sample
biases due to the loss of smaller debris. Unfortunately, lithics from the Isaac and Clarke excavation appear to have been lost (Wilshaw, 2012) and, thus, are no longer available for study.

4.2. Analyzed GC2 assemblage

In 1935–1936, the Peabody Museum acquired 241 GC2 obsidian artifacts from L.S.B. Leakey, at the request of then-Director Hugh Hencken, who sought a “strictly typical series representing the various ancient cultures of Kenya” (PMAE Accession File 36-6). All but two of the artifacts still had Leakey’s attribution to Upper Kenyan Aurignacian Phase a or b, which today correspond to Eburran Phases 3 and 4, respectively (Fig. 3). We sourced 239 obsidian artifacts: 121 (51%) from lower deposits (Eburran Phase 3) and 118 (49%) from the upper deposits (Eburran Phase 4). Thus, the assemblage is nearly evenly split between the phases, with only 2.5% relative difference. The total masses of the artifacts are also similar: 434.3 g in Phase 3 and 481.4 g in Phase 4—a 10% difference (Table 1). In addition, the proportions of artifact types identified in the phases, while not identical, are sufficiently similar to allow their comparison for our purposes (Table 2).

The Peabody’s sample consists largely of retouched artifacts (n = 203), with fewer cores (n = 31, including burnis) and 16 unretouched pieces. It is clearly biased, attested by the near-absence of unretouched flaking debris. However, retouched tools are often considered to be among the most portable elements of the toolkit transported by foragers. For example, Eerkens et al. (2007) report that, among hunter-gatherer populations of the North American West, obsidian retouched pieces typically exhibit greater source diversity and,

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**Table 1**
Summary of the obsidian sources for GC2 artifacts from the Eburran Phases 3 and 4 deposits. Additional details are available in the supplementary online materials.

<table>
<thead>
<tr>
<th>Obsidian source</th>
<th>Distance (km)</th>
<th>Elevation (m asl)</th>
<th>Eburran Phase 3</th>
<th>Eburran Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Eburru outcrops</td>
<td>20</td>
<td>2590</td>
<td>105 87%</td>
<td>93 79%</td>
</tr>
<tr>
<td>Mundui/Sonanchi</td>
<td>30</td>
<td>1950</td>
<td>11 9.1%</td>
<td>15 13%</td>
</tr>
<tr>
<td>Baixia Estate/Ilike</td>
<td>30</td>
<td>2030</td>
<td>3 2.5%</td>
<td>9 7.6%</td>
</tr>
<tr>
<td>Masai Gorge Rockshelter</td>
<td>35</td>
<td>2050</td>
<td>1 0.8%</td>
<td>1 0.8%</td>
</tr>
<tr>
<td>Menengai</td>
<td>35</td>
<td>2020</td>
<td>1 0.8%</td>
<td>1 0.8%</td>
</tr>
<tr>
<td>Hell’s Gate 1/Ololbutot 1</td>
<td>40</td>
<td>2100</td>
<td>1 0.8%</td>
<td>1 0.8%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>121 87%</td>
<td>118 87%</td>
</tr>
</tbody>
</table>

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**Table 2**
Summary of the typological classification of GC2 artifacts from the Eburran Phases 3 and 4 deposits. Additional details are available in the supplementary online materials.

<table>
<thead>
<tr>
<th>Simplified types</th>
<th>Eburran Phase 3</th>
<th>Eburran Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backed piece, complete</td>
<td>62 51%</td>
<td>54 46%</td>
</tr>
<tr>
<td>Backed piece, fragment</td>
<td>31 26%</td>
<td>21 18%</td>
</tr>
<tr>
<td>Core</td>
<td>11 9%</td>
<td>20 17%</td>
</tr>
<tr>
<td>Scraper</td>
<td>8 7%</td>
<td>11 9%</td>
</tr>
<tr>
<td>Core edge maintenance flake</td>
<td>6 5%</td>
<td>7 6%</td>
</tr>
<tr>
<td>Blade, outrepasse</td>
<td>2 2%</td>
<td></td>
</tr>
<tr>
<td>Flake fragment</td>
<td></td>
<td>1 1%</td>
</tr>
<tr>
<td>Retouched blade, complete</td>
<td></td>
<td>1 1%</td>
</tr>
<tr>
<td>Retouched blade, fragment</td>
<td>2 2%</td>
<td></td>
</tr>
<tr>
<td>Misc. retouched piece</td>
<td>1 1%</td>
<td>1 1%</td>
</tr>
<tr>
<td>Total</td>
<td>121</td>
<td>118</td>
</tr>
</tbody>
</table>

Fig. 3. Examples of sourced obsidian tools from the Eburran Phase 3 (left) and Phase 4 (right) deposits, showing that these tools, principally backed blades and lunates, decreased in size over time (backed blades shrank from 34 ± 11 mm to 27 ± 8 mm in length; Ambrose, 2002).
on average, are found farther from their sources, whereas unmodified flakes tend to reflect fewer, closer sources. Similar trends have also been noted by Conard and Adler (1997), Turq et al. (2013), and others among Middle Paleolithic assemblages across Western Europe. Retouched or “finished” tools, particularly backed microliths (like those that dominate Eburran assemblages) may also be more suited for the purposes of exchange between groups (Ambrose, 2002). Despite its shortcomings, our sample is therefore appropriate to explore obsidian source and landscape use in the early Holocene of the Central Kenyan Rift Valley.

Hivernel (1974) studied all of the remaining material known from Leakey’s excavations of Eburran Phases 3 and 4 at GC2, stored in various museums across the U.K. and Kenya. She reports a total of 1551 artifacts from Phase 3 and 1982 artifacts from Phase 4. Therefore, our analysis of 239 artifacts represents a ~5–9% sample of the known Eburran Phases 3 and 4 material excavated and retained by Leakey. In terms of absolute (rather than relative) size, our sample contains the largest number of obsidian artifacts with geochemical data and source attributions currently published for any Holocene LSA site in Kenya (cf. Merrick and Brown, 1984a, 1984b; Merrick et al., 1990; Nash et al., 2011; Ndiema et al., 2011).

4.3. Instrument and settings

We used a Thermo Scientific Niton XL3t GOLDD+ analyzer in this study. It is outfitted with a 2-W, Ag-anode tube to produce an incident X-ray beam. The tube’s voltage and current change in combination with different X-ray filters to optimally fluoresce elements in different portions of the periodic table. The elements of primary interest – the so-called “mid-Z” elements – were measured for 30–45 s using the “main” X-ray filter with a tube voltage of 40 kV and current of ≤50 μA. This model is also equipped with a 25-mm² silicon drift detector that has a resolution ≤155 eV. The X-ray beam has a diameter of ~8 mm. The internal camera facilitated positioning the artifacts over the beam, and a test stand was used for the most stable measurement conditions.

4.4. Correction and calibration

Measured X-rays must be “corrected” for various physical phenomena in a specimen (X-ray absorption and attenuation, secondary and tertiary X-ray fluorescence, photoelectric emission, and so on). We used the fundamental parameters (FP) approach, which has been demonstrated to yield greater accuracy than empirical methods (Heginbotham et al., 2010). The instrument has a factory-set calibration tested with certified reference materials (CRMs) principally from the United States’ National Institute of Standards and Technology. We “fine-tuned” our data with a custom calibration tailored to the datasets of Brown et al. (2013). Specifically, to maximize compatibility with Brown et al. (2013), we used 27 specimens originally analyzed in their study. As documented in Frahm et al. (2017), twelve of the specimens were used as calibration standards, and the other fifteen served as secondary standards to evaluate our custom calibration and show how well the calibrated pXRF data replicates values in Brown et al. (2013). As shown in Fig. 4, pXRF data for the mid-Z elements are highly correlated to their wavelength-dispersive XRF (WDXRF) data. After calibration, slopes of the best-fit lines nearly equal 1. As established in Frahm et al. (2017), these elements exhibit only small differences (2–4% relative) compared to the data in Brown et al. (2013), and our calibration allows direct compatibility between our pXRF data and those in Brown et al. (2013).

4.5. Procedures for small artifacts

Many of the GC2 artifacts are small, a known challenge for XRF techniques (e.g., Davis et al., 1998; Eerkens et al., 2007; Shackley, 2011, 2012; Freund, 2014; Escola et al., 2016). Consequently, archaeologists typically exclude small artifacts from pXRF-based sourcing studies (e.g., Sheppard et al., 2011; Golitko, 2011; Goodale et al., 2012; Kellett et al., 2013; Galipaud et al., 2014; Coffman and Rasie, 2015; Millhauser et al., 2015). Frahm (2016), though, developed and tested two methods for pXRF-based sourcing of small obsidian artifacts using well-measured mid-Z elements with similar X-ray energies. We used one of these techniques to minimize errors associated with XRF of small lithic size classes. In short, elements such as Rb, Sr, Y, Zr, and Nb are well measured using XRF and, due to their similar characteristic X-ray energies, are affected by small specimen sizes in the same way, meaning that ratios between them can largely cancel out the size effects. Sr occurs at very low concentrations in most Kenyan obsidians, so its utility for discerning sources is small. Therefore, we base our source identifications on ratios of Zr, Y, and Nb to Rb. As a result, these identifications are based on four independent variables while size effects have been minimized.

Fig. 5 is a scatterplot of Zr/Rb, Y/Rb, and Nb/Rb. Note that, for four of the six identified obsidian sources, we plot not only the WDXRF values of Brown et al. (2013) but also our pXRF data for geological specimens from the same sources. We also plot their WDXRF data and our pXRF data for seven additional sources that were not identified among the GC2 artifacts. Analyzing geological specimens offers an extra check on our ability to reproduce the values in Brown et al. (2013). The published and our newly measured values directly overlap in this scatterplot, demonstrating how well our measurements duplicate those from Brown et al. (2013). Thus, we have high confidence in our identifications, and all of these data are included in the supplementary material.

5. Results

Here we document our estimates of occupation intensity as well as the identified obsidian sources and differences in their exploitation between the two site phases. It is worth noting that Central Rift Valley obsidian sources principally occur as discrete primary outcrops – more often as localized flows, less often as blocks in welded tuffs and ignimbrites – rather than as secondary deposits of transported nodules (Ambrose, 2012). There is, of course, variability in the surface expressions of these sources: some are obsidian flows that extend ~2000 m, while others are exposures < 200 m². On occasion, where obsidian is exposed on a hillside, there is a colluvial scatter across the slope. The regional topography, however, limits the alluvial transport of obsidian (i.e., blocks cannot escape closed basins without outlets via gravity or water transport). Particularly during the AHP, when the lakes greatly expanded, secondary deposits more than a few kilometers from the primary sources would have been underwater. Secondary obsidian deposits at the base of Mt. Eburru attest to this. Given the lack of opportunities for obsidian to be spread over large areas by natural processes, we have confidence in the collection locations.

5.1. Archaeological measures of occupation duration and intensity

Table 3 synthesizes artifact abundance and accumulation data for GC2, based on material from the 1964 Isaac and Clarke excavations and on age estimates from inferred sedimentation rates calculated by Ambrose (1984). In this sample, the proportions of retouched tools and total lithic debris differ significantly between the Eburran Phase 3 and Phase 4 deposits (χ² = 101.24, p < 0.01). These data show that the Eburran 3 strata (spits #1–13) have lower numbers of retouched tools (n = 322) but a higher artifact volumetric density (2953/m³), whereas Eburran 4 strata (spits #14–37) show more retouched tools (n = 407) but a lower artifact volumetric density (1034 artifacts/m³). Therefore, the retouched tool-to-artifact volumetric density ratio is 0.1 for the Eburran Phase 3 strata and 0.4 for the Eburran 4 strata. Although these numbers should be regarded with caution because of the many assumptions underlying them, estimated artifact discard rates are nearly
twice as high in the Eburran Phase 3 levels (∼6.2 artifacts/year) as in Eburran Phase 4 (∼3.2 artifacts/year), implying that more intensive occupation occurred earlier rather than later in the site’s history.

These findings suggest lower intensity occupations (i.e., fewer artifacts discarded per year) and increased mobility (i.e., relatively fewer retouched tools) during Eburran Phase 4 relative to Eburran Phase 3 at GC2. Such results do not support Ambrose’s (1984) original interpretation of GC2’s occupation history (our Hypothesis #2) but do support interpretations that drier, more open habitats associated with Eburran Phase 4 structured settlement strategies (Hypothesis #1). We would expect greater occupation intensity during Eburran Phase 3 to correlate with increased lithic reduction intensity. Testing this hypothesis, however, is difficult given the available sample, which is dominated by backed pieces that are replaced, not resharpened, during their use (Hiscock, 2006). Cores are rare and mostly (n = 30; 97%) made on relatively thin blade segments that have little potential for extensive reduction prior to discard. While Goldstein (2014) provides a useful approach to estimating the extent of endscraper reduction, many of the GC2 artifacts were made on blade blanks that were snapped, perhaps deliberately, so comparisons of endscraper size at discard to reconstructed original blade length provides a poor estimate of reduction intensity.

Obsidian source identification provides a means to assess the shape and size of the territory used by Eburran Phase 3 and 4 foragers. For the more intensive Eburran Phase 3 occupations, we predict increased reliance on local sources and use of a greater diversity of sources than in Phase 4. Toolstone from these diverse obsidian sources may have been acquired either by direct access or through contact with neighboring groups.

5.2. Identified obsidian sources

Six obsidian sources are reflected among the artifacts (Figs. 6 to 8). The most abundant source is also the closest: Mt. Eburru, ∼20 km from GC2, is the source for 79–87% of the artifacts in the two phases. There are multiple primary outcrops and secondary deposits on the north-eastern slope of Eburru (Brown et al., 2013), including a Late Holocene obsidian quarry (i.e., GsJj50) discussed by Goldstein and Munyiri (2017). At this quarry, which lies at ∼2570 m asl, excellent quality obsidian crops out as very large blocks, and there is a sizable debris scatter from reducing them (Brown et al., 2013; Goldstein and Munyiri, 2017). Above this quarry, up to elevations of ∼2600 m asl, there are additional outcrops, some with quarrying debris (Brown et al., 2013). Below it, as far as ∼4–5 km to the northeast, there are a few outcrops of low-quality obsidian as well as secondary deposits, specifically water-rolled, -rounded, and -abraded cobbles within lacustrine sediments (Brown et al., 2013). The obsidian textures that occur in the GC2 tools appear more consistent with the high-elevation quarrying sites (i.e., “quality is excellent,” Brown et al., 2013) than low-elevation deposits (e.g., “granular,” “flow banding and small phenocrysts are common,”
which volcanic tuff geological unit extends at least several hundred meters (Brown et al., 2013). Blocks of sediments, that contains fair-quality obsidian as loose, distinguishable exposures ~3 km apart (Brown et al., 2013). The Lake Sonanchi Crater estate has excellent-quality obsidian blocks, occasionally half a meter in size, accessible within the crater wall (Brown et al., 2013). The “Baixia Estate/Ilake” exposure is a ~40-m-long ridge, partly covered by lacustrine sediments, that contains fair-quality obsidian blocks, occasionally half a meter in size, accessible within the crater wall (Brown et al., 2013). The “Baixia Estate/Ilake” exposure is an isolated outcrop of pre-dominantly low-quality obsidian in small nodules (Brown et al., 2013). Thus, we hypothesize that “Baixia Estate” represents the origin of this obsidian variety. The “Masai Gorge Rockshelter” source is a chill zone (i.e., where the lava rapidly cooled via contact with the existing rock) exposed in a cliff face (Brown et al., 2013). The “Menengai” obsidian source is exposed in a caldera wall, where fair-quality obsidian seams occur throughout pumiceous layers (Brown et al., 2013). Lastly, the “Hell's Gate 1/Ololbutot 1” obsidian source has two elementally indistinguishable exposures ~6 km apart. The “Hell's Gate 1” exposure is a chill zone in a cliff wall, and the observed material was “very poor obsidian for artifact manufacture, having many inclusions” (Brown et al., 2013). The “Ololbutot 1” facies, however, consists of large blocks, occasionally a meter in diameter, some of which are excellent quality (Brown et al., 2013). Consequently, we presume that “Ololbutot 1” was the exposure exploited in antiquity. Note that, for both the Baixia Estate/Ilake and the Hell’s Gate 1/Ololbutot 1 obsidian varieties, the higher-quality obsidian exposures are marginally closer to GC2, meaning that we are also using the more conservative geographic origins.

**Table 3**


<table>
<thead>
<tr>
<th></th>
<th>Ebunan 3</th>
<th>Ebunan 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spit numbers</td>
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<td>14–37</td>
</tr>
<tr>
<td>Excavated area (m²)</td>
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<td>2</td>
</tr>
<tr>
<td>Excavated thickness (m)</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Excavated volume (m³)</td>
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<td>4.6</td>
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<tr>
<td>Minimum age (yr BP)</td>
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<tr>
<td>Age span (yr)</td>
<td>1244</td>
<td>1482</td>
</tr>
<tr>
<td>Artifacts/year</td>
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</tr>
<tr>
<td>Retouched tools (n)</td>
<td>322</td>
<td>407</td>
</tr>
<tr>
<td>Debris (n)</td>
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<td>4351</td>
</tr>
<tr>
<td>Artifact total (n)</td>
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<td>4351</td>
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<tr>
<td>Retouched tools (%)</td>
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<td>8.6</td>
</tr>
<tr>
<td>Artifacts volumetric density (artifacts/m³)</td>
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<td>1034</td>
</tr>
<tr>
<td>Retouched tools: artifact volumetric density</td>
<td>0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

“opaque green with a granular texture,” Brown et al., 2013). Given this and that there is evidence of extensive quarrying at the outcrops, our working hypothesis is that the GC2 artifacts are most likely to reflect acquisition from these quarrying sites or similar ones.

Five obsidian sources are supplementary to Mt. Eburrux, all ≥30 km from GC2. The “Mundui/Sonanchi” source has two chemically indistinguishable exposures ~3 km apart (Brown et al., 2013). The “Mundui Estate” exposure is a ~40-m-long ridge, partly covered by lacustrine sediments, that contains fair-quality obsidian as loose, “football-sized blocks... with numerous pumice inclusions” (Brown et al., 2013). The “Lake Sonanchi Crater” exposure, however, has excellent-quality obsidian blocks, occasionally half a meter in size, accessible within the crater wall (Brown et al., 2013). The “Baixia Estate/Ilake” source consists of two obsidian exposures, approximately ~9 km apart, that cannot be elementally distinguished. The “Baixia Estate” facies has “very high quality obsidian” exposed in a road cut into a quarry, in which volcanic tuff containing obsidian blocks was extracted, and this geological unit extends at least several hundred meters (Brown et al., 2013). In contrast, the “Ilkek” exposure is an isolated outcrop of predominately low-quality obsidian in small nodules (Brown et al., 2013). Consequently, we presume that “Ololbutot 1” was the exposure exploited in antiquity. Note that, for both the Baixia Estate/Ilake and the Hell’s Gate 1/Ololbutot 1 obsidian varieties, the higher-quality obsidian exposures are marginally closer to GC2, meaning that we are also using the more conservative geographic origins.

### 5.3. Diachronic view

Within our sample, both phases are dominated (~79–87%) by the closest obsidian source (Mt. Eburrux), which lies at or near the margin (~20 km) of what is often considered the daily range for foragers (e.g., Surovell, 2009). In both phases, almost all of the artifacts (~98–99%) came from the three obsidian sources: Mt. Eburrux, Mundui/Sonanchi, and Baixia Estate/Ilake, all ~30 km or less from GC2. Each of the other three sources that are ≥30 km away – Masai Gorge Rockshelter, Menengai, and Hell’s Gate 1/Ololbutot 1 – is reflected by a single artifact. Of these three sources, the farther two only occur in Phase 3, and the nearest one only occurs in Phase 4. However, given the abundance of Mt. Eburrux obsidian (20 km away), the mean source-to-site distances in both phases are essentially the same: 21.4 ± 3.8 km in Eburrux Phase 3 and 22.1 ± 4.1 km in Eburrux Phase 4. Note that these values use linear distances between GC2 and the sources. An
actual path on the ground between this site and each source would be longer. Even without Mt. Eburru, the difference between the phases overlaps within a standard deviation: 30.9 ± 2.7 km during Eburran Phase 3 and 30 km (i.e., these sources are roughly equidistant) during Eburran Phase 4. Still, the two most distant obsidian sources – Menengai (35 km away) and Hell’s Gate 1/Ololbutot 1 (40 km away) – are only found among artifacts from the earlier Eburran Phase 3.

Based on our estimates of artifact discard rates and retouched tool frequencies, we expect the more intensive Eburran 3 occupations to sample a more diverse array of obsidian sources, as the diversity of toolstone tends to increase as greater portions of the landscape are used during more prolonged occupations. We also expect the Eburran 3 occupations to show increased reliance on local (> 20 km distant) sources. This is, in part, due to the inferred greater occupation intensity as well as the drier condition during Eburran Phase 4, as suggested by the fauna, which may have compelled larger home ranges and, thus, more interactions with distant areas. Neither expectation is strongly supported by our available data. Artifacts from Phase 3 originate from more sources (n = 5) relative to Phase 4 (n = 4); however, this does not significantly differ from an even or random distribution between the two phases (χ² = 0.45, p = 0.83). Similarly, more of the Eburran 4 sample originated from non-local obsidian sources (21.2%) relative to the Eburran 3 sample (13.2%), but this difference is not supported at the p < 0.05 level (χ² = 2.67, p = 0.10).

We note also that that there is no significant difference in the elevation of the sources used between Phases 3 and 4. Overall, the mean elevations for these two phases are similar, with means overlapping at one standard deviation: 2509 ± 209 m asl in Eburran Phase 3 and
2461 ± 250 asl in Eburrn Phase 4. These mean values are skewed by the abundance of Mt. Eburru obsidian at 2590 m asl. Excluding Mt. Eburru from the calculations results in lower mean altitudes: 1979 ± 47 m in Eburrn Phase 3 and 1983 ± 41 km in Eburrn Phase 4. These elevation ranges, however, clearly overlap within a single standard deviation. It is also worth noting that both the highest obsidian source (Mt. Eburru at ~2590 m) and lowest source (Mundui/Sonanchi at ~1950 m) were the two most commonly exploited, at least based on the Peabody Museum’s sample.

6. Discussion

Paleoenvironmental proxies from GC2 and neighboring lakes indicate a habitat shift from a more wooded, closed nearshore setting during Eburrn Phase 3 to a more open, grassy, and drier setting during Eburrn Phase 4. The results here suggest that this change in habitat was paralleled by a decline in occupation intensity over time. Given the apparent preference for occupations near the forest-savanna ecotone by Eburrn foragers, the GC2 pattern can reasonably be interpreted as a apparent preference for occupations near the forest-savanna ecotone by Eburrn foragers.

In short, changes in the settlement pattern appear to have had no measurable impact on the types of toolstone being used, at least within the vicinity of the site and would have been available to its past occupants. However, despite being able to attribute all 239 GC2 artifacts in our sample to their sources, our results indicate no significant differences between Eburrn Phases 3 and 4 in terms of the diversity of sources used, use of non-local sources, or altitude of the outcrops used. In short, changes in the settlement pattern appear to have had no measurable impact on the types of toolstone being used, at least within the biased sample that Leakey sent to the Peabody Museum.

The lack of temporal differences in obsidian sources may indicate the resilience of Eburrn foraging strategies and the ability of a cultural preference for particular types of stone to overcome changes within the local environment that would have impacted its availability. While speculative, the persistent use Mt. Eburru obsidian observed in Eburrn Phases 3 and 4 at GC2 may indicate the early stages of a wider phenomenon of the preferred use of this lithic material at many Kenyan and Tanzanian sites, a pattern that reached its apogee with Elmenteitan pastoralist groups. Mt. Eburru obsidian is the dominant lithic material at Elmenteitan sites regardless of source distance (at times ~200 km away), suggesting regular mechanisms for the supply and movement of this toolstone, to the near-exclusion of contemporary “Savanna Pastoral Neolithic” groups, who relied instead on the obsidian sources south of Lake Naivasha ~10–20 km from Mt. Eburru (see Goldstein and Munyiri, 2017 for review). This pattern has been interpreted as an example of controlled access to specific resources or landscape facets via social and/or physical means (cf. Robertshaw, 1990; Ambrose, 2012; Goldstein and Munyiri, 2017). The antiquity of this pattern is difficult to discern, particularly as the exploited obsidian sources for Eburrn Phase 5 assemblages (which precede the Elmenteitan strata) have not yet been determined. Limited support for this speculative scenario may be found in the Lake Victoria basin ~200 km away, where Mt. Eburru obsidian accounts for about 25% of the obsidian during the early Holocene (when only foragers are present) but 53% of the late Holocene assemblages made by foragers and 67% of the studied pastoralist Elmenteitan sites (Merrick and Brown, 1984a, 1984b; Frahm et al., 2017). These data may suggest either (a) increased use over time of Mt. Eburru obsidians by foragers in the Lake Victoria basin or (b) obsidian acquisition by late Holocene foragers through some form of interaction with Elmenteitan groups.

7. Conclusions

The Naivasha-Nakuru Basin of Kenya’s Central Rift Valley is a region that is not only highly sensitive to climatic changes but also one of the world’s most obsidian-rich landscapes, allowing us to investigate the relationship between environmental change and behavioral adaptations over the course of the Holocene. The effect of these changes on Eburrn LSA hunter-gatherer populations has been one such focus of research in past studies, in particular those of Ambrose and colleagues (e.g., Ambrose, 1984, 1986; Ambrose and Sikes, 1991). GC2 serves as the type site for the early to middle Holocene Eburrn Phases 3 and 4, which likely sample an earlier, more humid interval and a later, drier one, respectively. Our analysis of occupation data for GC2 suggests a greater intensity during the more humid Eburrn Phase 3, when the lake’s shoreline was likely closer to the site than it is at present. As the lake retreated (and, with it, the site’s position at an important ecotone), occupation intensity declined, as measured by both the lower frequency of retouched tools and by the reduced artifact discard rates in the Eburrn Phase 4 deposits.

Using pXRF, we analyzed 239 obsidian artifacts from GC2 housed at Harvard’s Peabody Museum of Archaeology and Ethnology and attributed them to six obsidian sources using a WDXRF database published by Brown et al. (2013). Comparison between the two phases suggest that the site’s occupation history or local environment had no discernable effect – at least within this sample – on the variety or range of obsidian sources used for tool manufacture, with the closest source (Mt. Eburru at ~20 km away) consistently used to meet the supply demands for lithic raw material. This implies that the demand for this material
outweighed any changes in the difficulty of its acquisition by GC2 occupants. Speculatively, the GC2 data might also mark the beginning of the widespread use of Mt. Eburrn obsidian by groups of foragers throughout central and southern Kenya and northern Tanzania. Testing such a hypothesis requires, in part, a new, more extensive program to determine the obsidian sources exploited by Eburrn foragers. Our results here demonstrate the potential for such analyses and underscore the amount of work that remains to be done.

Acknowledgements

Frank Brown passed away while this manuscript was under review, and given the importance of his decades of work to the success of this project, we wish to dedicate this paper to his memory. Harry Merrick also generously contributed the collection of geological obsidian specimens used for our calibration to Brown et al. (2013). Viva Fisher (Senior Registrar), Kara Schneiderman (Director of Collections), Diana Loren (Director of Academic Partnerships) and Emily Pierce Rose (Curatorial Assistant for Academic Partnerships) facilitated access to the artifacts in the Peabody’s collections. The Peabody’s artifacts were a gift of the East African Archaeological Expedition via Dr. L.S.B. Leakey, F.S.A., 1936. Charles Nelson generously provided his unpublished data on the total number of artifacts recovered from the 1964 Isaac and Clarke excavations. Ravid Eskhait provided valuable research support for the pXRF and lithic analyses, and she was key in getting this project started. Support was provided by the American School of Prehistoric Research, Harvard University and the University of Minnesota’s Department of Anthropology, Department of Earth Sciences, and Institute for Rock Magnetism. The pXRF instrument utilized for this study is part of the research infrastructure of the University of Minnesota’s Institute for Rock Magnetism (IRM). Funding for the instrument came, in part, from the University of Minnesota’s Grant-in-Aid of Research, Artistry, and Scholarship (GIA) Program, awarded to Joshua Feinberg, Gilbert Tostevin, and Kyungsoo Yoo.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2018.01.042.

References
