Picking up The Pieces: Reconstructing Lithic Production Strategies at a Late Holocene Obsidian Quarry in Southern Kenya

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ABSTRACT
Use of particular lithic quarries by different cultural groups is a prominent feature of the Pastoral Neolithic period in southern Kenya (ca. 3200–1400 B.P.), when lifeways based on herding domesticated livestock spread through eastern Africa. Here, I present lithic attributes from the recently excavated Elmenteitan Obsidian Quarry assemblage to examine the site’s role in an obsidian distribution network spanning southwestern Kenya. Evidence from the quarry reflects intensive preparation of blade cores and blade reduction. Changes in platform size, flake scar orientation, curvature, and cortical rates through the reduction sequence permit a preliminary reconstruction of Elmenteitan core production strategies that can serve as a basis for regional comparative studies. Uniformity in blade core design and reduction strategy suggests highly organized use of the quarry and supports its role as a production center for regional exchange. Results inform regional debates and contribute to a growing literature on the potential of quarry archaeology.

Introduction
Lithic quarries—places where people extracted and prepared stone tools—were important centers of social and economic production for stone tool-using populations. Behaviors at a quarry reflect expectations for the transport and use of stone on the landscape (Beck et al. 2002; Dillian 2007; Ericson 1984; Holmes 1919; Johnson 1987; Raab et al. 1979). Exchange networks, subsistence strategy, seasonality, social structures, mobility strategy, and perceptions of future risk all affect the preparation and design of stone cores at archaeological quarries (Andrefsky 1994; Bamforth 2006; Beck et al. 2002; Brantingham 2003; Messineo and Barros 2015; Shott 2015; Torrence 1986; Tripcevich and Contreas 2013). If the copious remains of these activities can be used to reconstruct broader tool-use strategies, they will provide a robust dataset for investigating socio-economic dimensions of prehistoric societies.

Excavation and dating of dense, often undifferentiated palimpsests of stone tool debris can be daunting. Archaeologists often cite additional difficulties in cataloging and analyzing the thousands of pieces of non-diagnostic lithic debris these projects produce (Ericson 1984; 2; Singer 1984). Nevertheless, archaeologists have produced a body of literature presenting methodological advances and building on them to apply analyses toward addressing regional or archaeological issues (Beck et al. 2002; Dillian 2007; McCoy et al. 2011; Skarpelis et al. 2017; Tripcevich and Contreas 2013). Contributions from new regions and social, economic, and technological contexts are needed to further develop analyses of quarry assemblages and realize the potential of these datasets within anthropological archaeology.

In this paper, I present analyses of a debitage assemblage related to core preparation and blade reduction at an obsidian quarry site used by ancient herders in southern Kenya. The analysis is intended to provide a quantitative characterization of blade core design, preparation, and reduction sequences at this site as a necessary starting point for comparative studies in the region. Located in the Central Rift Valley, the Elmenteitan Obsidian Quarry on top of the volcanic Mt. Eburrur was used by the Elmenteitan culture-historical group of early cattle herders from 3000–1400 B.P. (Goldstein and Munyiri 2017). Geochemically distinct green-hued obsidians from Mt. Eburrur dominate lithic assemblages at Elmenteitan sites across southern Kenya (FIGURE 1), suggesting that the quarry was at the center of a sustained exchange or distribution system (Ambrose 2001; Robertshaw 1988). The Elmenteitan Obsidian Quarry plays a prominent role in discussions of early herder identities, social systems, and exchange networks, yet very little is known about human behaviors at this site (Ambrose 2001; Gifford-Gonzalez 1998a, 1998b; Marshall et al. 2011; Simons 2005).

The composition and economic needs and expectations of groups using the quarry should be reflected in patterns of nodule selection, core design, core management, and blade reduction strategies. This analysis uses simple flake attributes and metrics to infer these patterns based on a sample of 1941 lithic artifacts recovered from excavations at the Elmenteaitan Obsidian Quarry in 2014 (Goldstein and Munyiri 2017). Although this is a small sample size for a lithic quarry, it is enough to begin building models for Elmenteitan lithic organization that are relevant for addressing social and economic questions related to the spread of food production in eastern Africa.

The Pastoral Neolithic (PN)
Lifeways that were economically and ideologically centered on the ownership and movement of cattle originated in
the eastern Sahara by ca. 8000 B.P., before the adoption of domesticated crops (Marshall and Hildebrand 2002). Herders adopted mobility strategies involving both residential relocation and logistical herding of livestock to access good pastures, salt licks, and water, or to move them away from threats (Binford 1979). Lithic toolkits associated with herders migrating southward to escape desertification of the Sahara continue to reflect emphasis on blade, bladelet, and microlith production (Cremaschi and Di Lernia 1999; McDonald 1998).

Domesticated cattle first appear in the Lake Turkana Basin of northern Kenya between 5000–4000 B.P., along with goats and sheep from the Near East (Hildebrand and Grillo 2012; Marshall et al. 1984). A slow trickle of livestock southward into the Central Rift Valley of southern Kenya precedes the appearance of wide-spread herding traditions after ca. 3200 B.P. Herder sites remain typically small, likely representing short-term occupations; however, there are at least a few more substantial settlements at sites like Ngamuriak (Robertshaw 1990), that may represent long-term occupations or large ceremonial aggregations.

Diverse socio-economic dynamics underlie the spread of pastoralism in southern Kenya, with a mosaic of hunter-gatherer and food-producer populations co-existing through the Late Holocene. One group of sites with clear evidence for economies based on domesticated animals is the Savanna Pastoral Neolithic (SPN). The SPN seems to encompass a range of groups with diverse ceramic decorations, different degrees of wild fauna exploitation, and variable lithic tool forms and production styles (Ambrose 1998, 2001; Bower et al. 1977; Marshall et al. 2011; Wandibba 1977). There are also broad shared characteristics: SPN materials are found in association with cairn burials and open-air sites in the savannas. While SPN sites feature variable raw materials, obsidian at SPN sites is sourced to localities around southern and western Lake Naivasha (Ambrose 1982, 2001; Bower 1991; Merrick and Brown 1984). These source-groups are only a few kilometers south of Mt. Eburru, which would become the primary obsidian source for herders associated with a new set of Elmenteitan traditions (Ambrose 2001; Robertshaw 1990).

The Elmenteitan Tradition of the Pastoral Neolithic

Unlike the SPN, the Elmenteitan appears as a more consistent and uniform cultural entity that first appears ca. 3000 B.P., and persists until the spread of iron technologies around 1400 B.P. Elmenteitan sites universally yield undecorated mica-tempered plainware with lugs and spouts, and these never co-occur with SPN ceramic styles (Ambrose 1982; Collett and Robertshaw 1983). Elmenteitan sites overlap with the SPN range, but extend further west to Lake Victoria and many Elmenteitan sites are located in the southwestern highlands, where SPN occurrences are absent (Ambrose 1984). Elmenteitan material is associated with rockshelter and crevice cremation burials, again diverging from SPN patterns (Ambrose 2001). Based on the multiple lines of evidence suggesting very real underlying social and economic differences between the SPN and Elmenteitan, Ambrose (1982) has argued that these categories may have an ethno-linguistic basis.

While SPN and hunter-gatherer groups frequently used obsidian from various sources, Elmenteitan groups largely ignored those sources in favor of geochemically discrete green-hued obsidian from Mt. Eburru, which makes up 70–90% of lithic assemblages at Elmenteitan sites up to 250 km away (Brown et al. 2013; Merrick and Brown 1984). Obsidian from Eburru thus has a regional distribution, or “terrane” (Elston 1992: 35), covering most of southwestern Kenya. Elmenteitan groups used obsidian from Mt. Eburru to produce large, broad, flat blades with heavily prepared striking platforms. Blades were intensively utilized with little modification, backed as knives, made into endscrapers, or segmented into smaller blanks for burins, bladelet cores, or other expedient tools (Ambrose 1984, 2001; Nelson 1980). Smaller blades were used to make backed geometrics, which remained common.
There are numerous qualitative differences between SPN and Elmenteitan toolkits, but there have been few quantitative comparisons. One important exception is the study by Ambrose (2002) that demonstrates that SPN and Elmenteitan sites consistently differ in terms of platform preparation styles, average striking platform size, and backed microlithic size distributions. More expansive debitage analyses are needed before it is possible to mount larger-scale comparative studies of PN lithic assemblages.

Identifiable fauna at Elmenteitan sites are usually dominated by domestic species (up to 99%), reflecting specialized pastoralism wherein most calories are derived from the milk, meat, and blood of herd animals (Marshall 1990; Simons 2004). Currently, there is no macro-botanical evidence for domesticated plants until the very end of the Pastoral Neolithic period. Isotopic evidence does suggest that Elmenteitan herders were likely cultivating and consuming plants foods to a greater degree than SPN herders (Ambrose and DeNiro 1986). In order to maintain such an economy, Elmenteitan herders (much like recent herding societies) would have needed to prefer the needs of their herds above all other economic concerns (Dahl and Hjort 1976). Frequency and intensity of group mobility would thus depend primarily on the distribution of high quality grasslands, which was unpredictable through space and time due to erratic rainfall regimes of the later Holocene (Gifford-Gonzalez 1998a; Marshall 1990).

One important dimension of Elmenteitan strategies may have been the formation of exchange networks that facilitated the distribution of high-quality obsidian cores (Ambrose 2001; Goldstein and Munyiri 2017; Robertshaw 1990). The cold and forested upper slopes of Mt. Eburru lack a perennial source of water other than sulfurous steam-vents, and were unlikely to have been visited as an “embodied” (Binford 1979) component of herder mobility. Use of domesticated donkeys offered increased flexibility in mobility and long distance transportation (Marshall and Weissbrod 2011). Structural differences between this type of economy and those of transhumant pastoralists, sedentary agriculturalists, and hunter-gatherers may have created novel pressures on raw material access and lithic production.

Maintaining access to a single obsidian source-group over such a distance and over such a deep length of time is believed to have involved considerable social organization, beyond expectations for simple down-the-line exchange (Ambrose 2001; Goldstein and Munyiri 2017; Robertshaw 1990). The cold and forested upper slopes of Mt. Eburru lack a perennial source of water other than sulfurous steam-vents, and were unlikely to have been visited as an “embodied” (Binford 1979) component of herder mobility. Use of domesticated donkeys offered increased flexibility in mobility and long distance transportation (Marshall and Weissbrod 2011). Structural differences between this type of economy and those of transhumant pastoralists, sedentary agriculturalists, and hunter-gatherers may have created novel pressures on raw material access and lithic production.

Quarry Archaeology

With few exceptions, pastoralist habitation sites in eastern Africa are small, single occupational sequence occurrences, yielding small lithic assemblages. With less than ten extensively excavated Elmenteitan sites, reconstructing Elmenteitan technological organization, land use strategies, and obsidian exchange might require new excavations at multiple sites across southern Kenya. A quarry site can, however, provide a very large lithic sample from relatively small-scale excavations. Theoretically, quarry samples encompass the strategic variation of groups using the site (Ericson 1981, 1984; Messineo and Barros 2015).

Different patterns of core production at a quarry as seen by archaeologists are a proxy for the nature of social interactions at a landscape level. Additionally, people in different environmental conditions, with different mobility strategies and economic practices, might modify their lithic technologies according to their specific needs. Patterns of core preparation thus reflect the social distance between those preparing cores, and those who will ultimately be receiving them across the landscape (Ericson 1981). In this framework, the intensity and variability of core preparation and reduction can be used to reconstruct exchange and interaction (Ericson 1984; Shott 2015; Topping and Lynott 2005), underlying socio-political systems (Bettinger 1982: 11; Bloxom 2011), and regional lithic technological organization (Andrefsky 2010; Bamforth 1990; Wallace and Shea 2006).

Materials and Methods

The Elmenteitan Obsidian Quarry

The Elmenteitan Obsidian Quarry is located at 2604 masl on the upper slopes of Mt. Eburru, a volcanic massif that extends from the Maus Escarpment into the Central Rift Valley just north of Lake Naivasha in southern Kenya (FIGURE 1). Unlike other obsidian quarries in the region and around the world, the Elmenteitan Obsidian Quarry does not have large surface exposures of obsidian debris that can be readily sampled. Rich volcanic soils and high rainfall at this altitude encourage rapid pedogenesis, which, in combination with colluvial deposition, causes the archaeological horizon to be stratified about 40 cm below the modern ground surface. Dr. Stanley H. Ambrose first discovered the site during surveys of Mt. Eburru in 1980, when it became apparent there were large deposits of obsidian debris eroding from road-cuts through the site. The first excavations at the site were conducted in 2014 (Goldstein and Munyiri 2017).

Based on available data from the limited excavations, activities at the Elmenteitan Obsidian Quarry appear to be spatially patterned. A large expanse of the site currently cultivation was designated “Area 1,” and excavations revealed discrete patches (10 and 15 m²) of dense archaeological material separated laterally by low density or sterile deposits (FIGURE 2). Archaeological material from Area 1 includes mixed obsidian debris, shaped and expedient stone tools, Elmenteitan ceramics, fauna, ochre, and charcoal. Unlike at habitation sites, only large bovid remains were present. The lithic toolkit was dominated by backed pieces, with no formal endscrapers and few domestic tools. Deposits in Area 1 have been interpreted as the result of numerous overlapping camping episodes by groups coming to the quarry (Goldstein and Munyiri 2017).

Area 2 is in an adjacent part of the site, with several surficial exposures of cobble- to boulder-sized obsidian. The archaeological horizon here is a 50–70 cm thick deposit of undifferentiated obsidian knapping debris in areas of soil development between obsidian exposures (FIGURE 2A). Excavations produced no materials other than obsidian, and very few worked pieces, but had a higher proportion of early-stage core shaping debris and greater variation in obsidian quality (Goldstein and...
Munyiri 2017). Area 2 was likely where obsidian was first extracted and processed. Due to the high proportion of obsidian nodules and knapped debris near the surface, the entirety of Area 2 is un-cultivated and left as forest.

_sampled contexts_

This analysis includes a sample of blades recovered from 4 m² of excavation in Area 1, and from a single square meter in Area 2. Excavations sampled in Area 1 are within one patch where it is clear that modern cultivation has not reached the buried archaeological horizon, and for which there are radiocarbon dates. Calibrated date ranges for charcoal samples from the top, middle, and bottom of the horizon fall between 2160 and 1996 CAL B.P. (OS-122182–122184), and so the entire deposit here was formed over at most 160 years, but possibly within a single generation (Goldstein and Munyiri 2017). Despite rapid deposition of materials, there were almost no detectable refits, making it difficult to reconstruct core reduction sequences through traditional approaches. Although no dating samples were recovered from Area 2, there were several single blade-to-core refits, and so this deposit may have formed from relatively few quar-rying episodes, possibly quite rapidly.

The few cores recovered were mostly expedient multi-plat- form bipolar flake cores. Lacking a large sample of Elmentei- tan blade cores, these analyses will focus on blade products as a proxy for the morphology and design of the parent core. Blades retain aspects of the core shape at the time of removal, as well as information about preparation techniques and reduction decisions that allow for a better reconstruction of core management through the sequence. Fortunately, both areas of the quarry site yielded large samples of blades with lengths from 20 cm down to 4 cm, reflecting a complete reduction sequence. Sampled context included 383 pieces identified as core preparation or modification elements (186 from Area 1 and 197 from Area 2) and 1206 blades (757 from Area 1 and 469 from Area 2) (SUPPLEMENTAL MATERIAL 1–2). All debris was measured, and a total of 372 complete and normally terminating blades were used in these analyses (FIGURE 3). This assemblage is small compared to quarry assemblages from other parts of the world, however it is the largest reported blade assemblage from a Pastoral Neolithic period site in the region.

Assemblages in Area 1 and Area 2 will be presented together, except in the very few cases where spatial differences were detected: these will be specifically noted. The comparison between these two assemblages from different parts of the quarry site will help test the hypothesis of the presence of discrete activity areas put forth in Goldstein and Munyiri (2017). If these areas did host different stages of the quarrying or core preparation process, they should yield quantitatively different technological signatures.

_attribute analysis_

Untouched debitage can be classified based on morphology and position within the process of core reduction. Here, the term “blade” refers to any complete flake that is at least twice as long as it is wide and/or has lamellar or prismatic flake scar patterns, following the standards from Ambrose (1984) and Slater (2016) (but see Collins [1999] also). Blade analysis included the following measures: length, width, thickness, weight following Andrefsky (2005:98–102); the size and form of preparation of striking platforms (Ambrose 2002; Shott et al. 2000; Slater 2016); dorsal flake scar orientations; total number of major flake scars on the dorsal surface (Johnson 1987: 193; Lyons 1994: 33; Magne and Pokotylo 1981); symmetry of the flake in plan-view as determined by the angle with which the distal end of the flake deviates from the vertical axis of the striking platform; overall curvature of the blade in the Z axis following Andrefsky (1986); and an estimate of the percentage of the dorsal flake surface that retains exterior weathered surface made to the nearest 10% interval (Andrefsky 2005: 106; Dibble et al. 2005) (SUPPLEMENTAL MATERIAL 3).

Combinations of these variables have been used in multivariate studies by Ingbar and colleagues (1989), Shott (1996), Bradbury and Carr (1999), and Shott and Habtzghi (2016) to develop continuum-based models for separating out mixed reduction strategies or testing the idea of production stages. The equations developed by Bradbury and Carr (1999) are of particular interest here, as they produce an equivalent measure of a flake assemblages place within a reduction

Figure 2. Modern land cover at the Elmenteitan Obsidian Quarry, with main quarry deposit (A) and surrounding “camp” areas (B) identified.
The primary goal of analyzing the lithic assemblage from the Elmenteitan Obsidian Quarry was to describe and reconstruct Elmenteitan blade core design, preparation, and reduction sequences. For blade cores (the foundation of Elmenteitan technological organization), the length of the blade release surface decreases as blades are removed. Blade length is, therefore, a useful correlate for the stage of a core in its reduction use-life. Changes in quantifiable attributes through reduction will similarly highlight the aspects of core morphology that are prioritized and the range of variability in core designs present. Considering that this is a quarry site where knappers had their pick of obsidian nodules of different qualities, the null expectation is that most of the variability will be found amongst the longest blades, which represent the earliest stages of preparing a nodule. As cores...
approach an intended shape and size, blade products should become more uniform.

Experimental projects examining flake and bifacial industries show greater rates of loss in core mass/size early in the reduction sequence, and much more gradual loss later, and these generalities likely hold for blade reduction as well (Dibble and Pelcin 1995). Blade core design, number and orientation of platforms, and regularity of maintenance will also affect results (Andreksky 2005; Lengyel and Chu 2016; Pelcin 1997). Initial identification of Elmenteitan core design and reduction is necessary to identify if such limitations apply here, and to inform future experimental projects that will, in turn, improve analytical protocols.

Results

Core preparation and modification debris

Obsidian can be found in nodules ranging in maximum linear dimension from 10 to 40 cm, and larger boulders are present that could provide variably sized spalls (Goldstein and Munyiri 2017). A total of 404 pieces were identified as being related to the modification of obsidian cores. Over 82% of this category is preparation debris, or flakes that were removed in the process of reducing an unprocessed obsidian nodule into a blade core. These are classified as early, middle, or later depending on their position within the relative chaîne opératoire for core preparation. Early stage preparation flakes are predominantly large cortical removals or are removals of angular protrusions or other undesirable morphological features from a nodule (FIGURE 4A, H). These flakes are thick, with large platforms and pronounced bulbs indicative of hard hammer reduction (Dibble and Pelcin 1995).

Middle stage preparation flakes reflect subsequent modification aimed at shaping or refining cores. Steep angles left behind by initial cortical removals were trimmed and removed at this stage, producing rounder and more regular faces for blade removal. This stage also includes the removal of large internal flaws and step or hinge fractures on the intended reduction face (FIGURE 4B, C, I), as well as the initial preparation of striking platforms, as evident in the frequency of half-prepared platforms reset with large core-tablet-like removals. There does not appear to be any systematic strategy at this stage of core preparation, as evidenced by variability in flake scar orientations and diverse shapes and morphologies of core modification debris (TABLE 1).

Late stage preparation debris is characterized by the formation of the actual blade release surface (FIGURE 4D–G). This involved the removal of opportunistic platforms from earlier stages or adjustment of striking platform angles. Platforms were prepared more seriously with heavy grinding and dorsal-proximal faceting. Platform removals from this stage can only be distinguished from those removed during later blade reduction by a lack of evidence for serial blade removals from the platform. There is continued effort through this stage of preparation to shape and smooth the core face by removing elevated edges. Small flaws, inclusions, or granular features that were missed previously were removed at this stage (FIGURE 4). Removals of blades after this point are not included as preparation debris.

Remaining core modification pieces are normal platform removals (n = 60), core tablet removals (n = 3), or heavy blows to remove stacked step fractures or deep hinge terminations (n = 9) (FIGURE 5). Unlike preparation flakes, these modifications appear to have taken place within the operational sequence of blade removal as part of core maintenance. Most platform removals are flanc removals initiated in parallel to the blade axis. They may also be oriented perpendicular to the prepared striking platform, removing parts of both the striking platform and core face (lames à crête after Brézillon [1968: 97]). Perpendicular platform removals are larger, and the large portion of the core face that they remove reflects relatively flat and straight flaking surfaces (FIGURE 5B, D, E, G, I). Parallel, or flanc, removals that serve to readjust striking platform angles and remove step fractures near the platform tend to be smaller and appear derived from cylindrical or pyramid cores (FIGURE 5C, I).

Flat surfaces adjacent and perpendicular to a primary blade release surface are often heavily prepared and set up as a platform. Most of these were removed without any attempt actually to remove blades from that platform; however, a few were clearly used as laterally adjacent blade release surfaces. Essentially, this indicates a regular practice of rotating the blade core to add a second platform/surface along a separate side of the core.

Blade production

Several complete blades from the Elmenteitan Obsidian Quarry had lengths of over 14 cm, and additional proximal and medial blade fragments appear derived from blades with lengths in excess of 20 cm. A greater proportion of the largest blades come from excavations in Area 1, although there are no differences in the overall distribution of blade sizes between the areas. Even with many very large blades, the average blade length at the site is only 5.85 cm, with most blades being between 6.5 and 3.8 cm. Blade widths (x̄ = 2.89 mm, SD = 1.53 mm) and thicknesses (x̄ = .88 mm, SD = .44 mm) are proportionately variable. This size distribution is identical to that from the distant Elmenteitan open-air habitation sites of Ngamuriak and Olupilikunya (Robertshaw 1990), again indicating that the Elmenteitan Obsidian Quarry assemblage represents the full blade core reduction sequences.

Length, width, and thickness share scalar relationships that are statistically significant at p < .05; however, all correlations are weak with low statistical power (SUPPLEMENTAL MATERIAL 4). Blade assemblages at Pastoral Neolithic habitation sites were found to have much stronger predictive correlations, especially between blade length and thickness (Goldstein 2014). Length-to-thickness was found to be the weakest relationship in the Elmenteitan Obsidian Quarry assemblage (Spearman rho = .50, r² = .41). Variation in these distributions suggests that there is little consistency in blade morphologies, and that any two blades of equal length, width, or thickness, could vary considerably in the other two dimensions. Blade production at the quarry site appears either to be less structured and systematic than at habitation sites, or to encompass a greater range of production styles or techniques.

Striking platforms

Striking platform preparation techniques appear to be strongly correlated with different PN cultural groups. Elmenteitan assemblages demonstrate a preference for intensive grinding of very small platforms with faceting along the proximal end of the dorsal surface (Ambrose 2002). Only 55% of
blades with intact proximal ends sampled exhibit dorsal-proximal faceting, and nearly 40% of these retained unprepared platforms. Of the prior group, platforms were smaller ($\bar{x} = 2.93$ cm$^2$), but still much larger than striking platforms from Elmenteitan habitation and rock shelter sites (Ambrose 2002). Unprepared platforms were much larger ($\bar{x} = 12.72$ cm$^2$). If smaller platforms increase raw material utility, the disproportionate representation of large platforms at the Elmenteitan Obsidian Quarry most likely reflects relaxed pressures for raw material conservation at a place of abundant material supply.

There is a positive ($r^2 = .65, p < .05$) relationship between platform width-to-blade width and platform thickness-to-blade thickness. This is consistent with observations by Ambrose (2002) that platform size is a predictor for blade cross-sectional area in Elmenteitan blades (FIGURE 6).

**Figure 4.** Core preparation flakes: A, H) early stage cortical removals; B, C, I) middle stage core shaping; D–G, J) mid-to-late stage removals preparing working face of the core. Scales are 1 cm.
Platform thickness is, however, a poor predictor for blade length in this assemblage. Given these relationships, manipulating platform width and/or thickness through different degrees of platform preparation could have given knappers the ability to create blades of a predictable width and thickness. Whether or not people making blades at the Elmenteitan Obsidian Quarry say actively tried to produce blades with specific cross-sectional areas is unclear.

**Flake scar orientations and count**

Parallel flake scar orientations are the most common scar pattern throughout the reduction sequence (85%). Blades were thus produced primarily either from single platform cores or from rotated cores where the blade removal faces do not intersect. Preference for single and rotated platform cores would be consistent with observations of blade cores at Elmenteitan sites in the Central Rift Valley (Nelson 1980) and in the southwestern highlands (Robertshaw 1990). Bi-directional flake scars, indicative of opposed platform cores account for only 9% of all complete blades. Radial, alternated, and oblique orientations occur in similar or lower frequencies throughout the reduction sequence (TABLE 2). Differences between the ratios of flake scar orientations for different blade length quartiles are not statistically significant ($\chi^2 = 11.712$, df = 12, Monte Carlo $p = .47$). A preference for single, or multiple non-intersecting, blade release surfaces appears to be a consistent design element in Elmenteitan blade cores imposed early in core shaping and maintained until core exhaustion.

Not surprisingly, larger blades tend to have more ($\geq 4$) dorsal flake scars (Spearman rho = .28, $p < .05$). Flake scar density as measured both by scar count relative to dorsal flake area and by flake mass (Bradbury and Carr 1999) shows a different pattern. Flake scar density remains low in early stages of reduction, and begins to exponentially increase at blade lengths of about 8 cm (SUPPLEMENTAL MATERIAL 5). This pattern is largely a product of scar count remaining steady at 2–3 as blades decrease from 8 cm to 2 cm in length.

**Blade symmetry and curvature**

Only 6.7% of complete blades had plan view asymmetries that exceeded 30 degrees, and none had asymmetries that exceeded 60 degrees. Blades over 7 cm had a higher rate of asymmetry, but this difference is not statistically significant ($\chi^2 = 15.609$, df = 12, Monte Carlo $p = .201$). This is again due to more opportunities for a blade to skew laterally on larger core surfaces. Once a sequence of parallel flake aerises is established, it provides a path of least resistance for force applied to the striking platform such that subsequent blades are also likely to be parallel. Blades become consistently straight by the time a core reaches 7 cm in height. Blade symmetry is one of the only attributes that had significant differences between excavation areas, with 33.8% of blades from Area 1 having some skew compared to only 17% in Area 2.

Blades exhibit low rates of dorsal-to-proximal curvatures. A total of 56.7% of complete blades had no measurable curvature (i.e., were flat). Another 12.3% of blades had curvatures below 10 degrees, making them effectively flat. This, too, is consistent with regional observations for Elmenteitan blades being typically flat, compared to blades made by contemporaneous groups of foragers and SPN pastoralists (Ambrose 2001; Nelson 1980). Only 31% of sampled blades had curvatures values high enough that they may reflect significant differences in the shape or structure of parent cores, and these tended to be the larger blades from early in the reduction sequence. Average blade curvature decreases as cores are reduced, with curvatures less than 10 degrees becoming typical by the time cores reach about 8 cm in height (FIGURE 7). Ensuing blades would have low curvatures through the reduction sequence, which would have required deliberate and constant preparation and maintenance of the core and blade release angles.

**Cortex**

Cortical coverage on blades is generally low, with average dorsal cortex at only 2.7%. Not surprisingly, large early stage blades have more dorsal cortex on average (7.2%) relative to other blade size classes. While blades of other size classes have less average dorsal surface covered in cortex, the frequency of blades with any dorsal cortex does not steadily decrease as cores are reduced. Instead, there are spikes in the number of blades with cortex at lengths of 6–4 cm, and the highest overall proportion of blades with cortex are 7–8 cm in length (FIGURE 8). Sample bias may contribute to this incongruity, as the 6–4 cm length range includes the most blades. Nonetheless, high rates of cortex-bearing blades later in the reduction sequence may be behaviorally meaningful.

Spikes in rates of dorsal cortex may reflect stages of core reduction in which it became necessary to re-orient the core and begin exploiting a second reduction surface that was still partially cortical, resulting in more blade removals capturing that cortex. This would fit with existing observations of mid-sized and smaller cores from Elmenteitan sites in the Central Rift Valley that show the addition of a second alternated platform that is not present on larger cores (Goldstein and Munyiri 2017; Nelson 1980).

**Reduction stages**

Measures of platform size, maximum width, and weight-controlled scar count were used to calculate percent complete values for all pieces so that they could be graphed in terms of their relative position within a reduction continuum (Bradbury and Carr 1999: 112). Figure 9 shows the calculated percent complete values for the different preparation or blade reduction stages identified through qualitative observations discussed above. There is significant overlap in the distributions for different stages that do show a gradual continuum of reduction from what was identified as early stage reduction though to serial blade removal. Note that despite this overlap, differences between the distributions are statistically significant (Kruskal–Wallis $\chi^2 = 182.3$, $p < .05$). Differences are
most pronounced between the earliest stages of core preparation and later stages of blade removal. The same pattern was produced by the equations presented by Shott (1996) (SUPPLEMENTAL MATERIAL 6).

Applying this measure provides an independent test of the stages identified. It is clear that this pattern would not be visible if the assemblage had not first been qualitatively sorted, supporting the combination of these approaches. Overlap

Figure 5. Platform removal flakes, arrows denote direction of removal relative to dorsal surface: A) cresting blade; B, D, E, G, H) perpendicular or lames à crête removal; C, I) parallel or flanc; F) removal of opposed platform.
between categories could be argued to be evidence for continuous reduction; however, I point to the major differences in overall distributions as evidence that the categories are partially supported. That being said, the middle and late stages of core preparation and initial blade removals are harder to disentangle. Even if these stages are real, it may not be possible to separate them metrically. This method is also constructive in that they identify outliers (such as the single outlier for Prep-2) that may be mis-categorized elements. It should be cautioned that these differences may be affected by small sample sizes for some of the categories.

Discussion

Core preparation and reduction at the Elmenteitan Obsidian Quarry

From these results, it is possible to reconstruct an operational sequence for core preparation and reduction at the Elmenteitan Obsidian Quarry in southern Kenya, which is relevant for understanding the organization of behaviors at the site. Diversity in flake scar orientations and flake size during initial nodule reduction, and the frequent removal of prepared (but unutilized) platforms suggest experimentation with edge angles and utilization faces in early phases of core preparation. This is followed by the first efforts to impose a shape by creating a striking platform. Once platforms were prepared, an initial phase of blade removal involving crested blade techniques also helped to shape cores. Based on blade lengths, blade reduction begins at core lengths of 15–12 cm, around which time cores converge on a single platform or fronted core morphology. This may be an archetypal Elmenteitan core design, being well suited to the production of long, broad, flat Elmenteitan blades. The 15–12 cm size range is exactly the size range for the longest blades at Elmenteitan sites and likely represents the size at which cores would have been exported from the quarry. Attribute analyses demonstrate overall consistency in the production of blades with the desired broad, straight, and flat morphology. These traits begin to be systematically implemented beginning at release surface lengths of 8 cm, and continue until cores are exhausted. Blades then are used as blanks for the production of most Elmenteitan tools, or are segmented to manufacture microblades or expedient cores-on-flakes (Nelson 1980).

Patterns in flake scar counts, cortical rates, and platform rejuvenations also hint at shifts in core design at different sizes or stages within the reduction sequence (Table 3). One of the most notable is a core rotation such that an adjacent side of the core can be exploited for blade reduction. This seems to occur at core heights of around 6 cm. The sudden increase in the frequency of smaller blades relative to larger blades may be due to this transition into simultaneous removals of blades from multiple faces of smaller cores. New platforms were typically set up such that removals along the new face did not intersect with the previous face.

![Figure 6. Bivariate plot of ratios of platform width to blade width and platform thickness to blade thickness for blades from GsJj50 (following Ambrose [2002]). Line represents the linear regression line for these data (Linear $r^2 = .65$, $p < .05$). Larger blades tend to have less stable platform size-to-blade size relationships.](image-url)

| Blade length | < 45 mm | 45–55 mm | 55–70 mm | > 70 mm |
|-------------|---------|----------|----------|---------|
| Scar pattern | Parallel | 105 | 77.8% | 60 | 75.9% | 55 | 69.6% | 57 | 73.1% |
| | Bi-directional | 14 | 10.4% | 6 | 7.6% | 7 | 8.9% | 8 | 10.3% |
| | Alternated | 10 | 7.4% | 6 | 7.6% | 7 | 8.9% | 10 | 12.8% |
| | Radial | 3 | 2.2% | 1 | 1.3% | 2 | 2.5% | 0 | 0.0% |
| | Oblique | 3 | 2.2% | 6 | 7.6% | 8 | 10.1% | 3 | 3.8% |
| Total | 135 | 79 | 79 | 78 |
| Scar count | 1 | 8 | 5.9% | 5 | 6.3% | 8 | 10.1% | 1 | 1.3% |
| | 2 | 48 | 35.6% | 24 | 30.4% | 21 | 26.6% | 9 | 11.5% |
| | 3 | 54 | 40.0% | 30 | 38.0% | 26 | 32.9% | 28 | 35.9% |
| | 4 | 22 | 16.3% | 15 | 19.0% | 13 | 16.5% | 26 | 33.3% |
| | 5+ | 3 | 2.2% | 5 | 6.3% | 11 | 13.9% | 14 | 17.9% |
| Total | 135 | 79 | 79 | 78 |
but occasional overshot blades or platform removals captured portions of an alternated core face, providing further evidence for this practice. High rates of cortex on mid-sized blades reflect reduction of a previously unworked surface.

Evidence from the quarry and comparisons with published assemblages from the Elmenteitan open-air sites of Ngamuriaq and Oloplukunya (Robertshaw 1990) and rock shelters in the Central Rift Valley (Ambrose 1984; Nelson 1980) indicate that the most common strategies were to add a laterally adjacent reduction face oriented at a 90 degree angle to the original or to add the new face in parallel to the first, but on the opposite side of the core as to create a naviform, or keel-shaped, morphology. Most likely, the exact decisions for the addition of new platforms depended on the shape of the particular nodules and which portions would most readily facilitate the removal of long flat blades. It is clear from the ubiquity of parallel flake scar orientations throughout the sequence that knappers, at least at the quarry, preferred to keep the reduction faces from intersecting and largely avoided bi-directional morphologies. Cores of various shapes eventually converged on a pyramidal morphology for bladelet production. Exhausted pyramidal cores and expedient cores-on-flakes are nearly the only types of obsidian cores found at any Elmenteitan sites, regardless of distance from the quarry. Combining this reconstruction of core reduction strategies with other published observations, it is possible to offer a tentative model for the Elmenteitan lithic operational sequence (FIGURE 10).

Figure 7. Average blade curvature by length size class. Error bars reflect standard error. Lower values reflect less curvature.

Figure 8. Frequency of blades with any dorsal cortex (dark) and percentage of sample with dorsal cortex (light) by blade length size class.
Use of the Elmenteitan Obsidian Quarry and implications for regional exchange

This quantitative study provides data on patterns at the quarry, but offers only limited insights into the broader system without an expanded comparative analysis. At present, it is possible to discuss a few relevant dimensions of the quarry pattern as it pertains to larger social and economic questions in Pastoral Neolithic archaeology. As best as can be reconstructed, the data on core morphology and reduction sequence present slightly conflicting perspectives on how the quarry was used and accessed. Some evidence supports more organized or centralized quarry use, whereas others point to a more open or heterarchical form of access.

While there is some flexibility in early core preparation, likely related to nodule-specific challenges, the trajectory for single platform, parallel orientation cores appears consistent and standardization is an expectation for a single group mass-producing cores for exchange (Arnold 1990; Root 1997). Furthermore, activity areas dedicated to obsidian extraction and early stage preparation were spatially separate from the living spaces, implying a consistent set of rules for spatial organization at the site. Quarry use was certainly organized to some degree, but it may not have been hierarchically managed (Burton 1984). Diversity in quarrying and early core preparation, as seen at the Elmenteitan Obsidian Quarry, has also been documented in cases of lithic production for non-centralized exchange in Hawai‘i (Cleghorn 1986), North America (Root 1997), and Peru (Tripcevich and Mackay 2011). Lithic remains analyzed here also cover only a small part of the quarry site, and indeed, potentially, a very narrow period. Expanded excavations might show additional variability not captured here.

Surveys of the area failed to detect any nearby habitation sites, and analyses of the ceramic temper suggests quarry use by multiple groups from across southwestern Kenya and the Central Rift (Goldstein and Munyiri 2017).

**Table 3.** Evidence for changes in core design through the operational sequence reconstructed from blade attribute analysis.

| Evidence                  | Core design change                           | When transition occurs (by blade length) |
|---------------------------|----------------------------------------------|-----------------------------------------|
| Core fragments and platform removals | Multiple blade reduction faces                | ~60 mm                                  |
| Dorsal-proximal faceting Platform size* | Consistently small platforms                | 80 mm                                   |
| Flake scar directionality Flake scar count | Consistently parallel dorsal scars           | ~70 mm                                  |
| Flake symmetry Curvature Cortex Bulb size / platform damage | Straight (no bend) flat or nearly flat High cortex rates Shift from hard hammer to punch | ~70 mm 80 mm > 100 mm, ~65 mm ~150 mm |
|                           |                                              | 75–70 mm                                 |
|                           |                                              | Consistently 2–3 dorsal scars            |< 60 mm                                  |

*(Goldstein and Munyiri 2017).
Reduction of cores down to exhaustion at the quarry exceeds anything that can possibly be described as “preparation,” possibly indicating that the site was used as a venue for practice or knowledge transmission. In some ways, the behaviors driving use of the Elmenteitan quarry are reminiscent of hunter-gatherer use of the Glass Mountain quarries in California, USA, wherein quarrying was carried out by specialists who travelled to the quarry (Dillian 2007). In that example, obsidian was used for ritual production rather than utilitarian implements, but the cultural value placed on obsidian from a
specific source does mirror the Elmenteitan use of glass from Mt. Eburru. The Chivay obsidian quarry in the highlands of Peru and its related network of regional obsidian exchange present another structural comparison that fits better with the role of the Elmenteitan Obsidian Quarry as a regional production center (Tripcevich and Mackay 2011).

In the case of the Elmenteitan, cores, core modification debris, and platform removals are present at distant habitation sites (Robertshaw 1990, 1991), indicating that people were receiving cores and not just blades from reduction at the quarry. Given the large (15 cm) blades at sites like Ngamuriak and Olopolokunya, herders living between 70 and 100 km from the quarry had fairly early-stage access to large cores. Even sites like Gogo Falls and Wadh Lang'o over 200 km away were receiving cores that were at least 10–12 cm long.

Communities receiving obsidian cores had agency to re-orient or modify the design of cores they received. Using the same methods applied here, it should be possible to detect those changes and assess whether local communities in different micro-environments were altering cores to meet localized needs or strategies. The operational sequence identified for the quarry may hold true across the Elmenteitan, which would support models of more economic uniformity and social integration within this entity (Ambro 2001; Marshall et al. 2011). Regional variation in core reduction strategies across southern Kenya’s diverse environmental zones would, alternatively, indicate that the uniform core types produced at the quarry were made by individuals or communities that were socially distant from or unfamiliar with the needs of distant recipients. In this case, the Elmenteitan groups may have been more economically diversified than is currently assumed, possibly interacting with hunter-gather-fisher communities, as has been proposed for Elmenteitan sites in the Lake Victoria Basin (Chritz et al. 2015). Differentiating between these possibilities is important, as they have different implications for social structures among early pastoralists, a topic which has so far been elusive (Gifford-Gonzalez 1998b, 2017).

Implications for quarry archaeology

Comprehensive discussions of raw material transport costs and behavioral patterns for hunter-gatherers provide a useful frame of reference for understanding the Elmenteitan pattern, which does not fit the models they propose (Beck et al. 2002; Brantingham 2003; Elston 1992; Shott 1996, 2015). One major reason may be access to domesticated donkeys that helped people move higher volume of obsidian further on the landscape. Another issue is that many existing quarry studies are primarily concerned with bifacial industries and societies whose mobility was organized in fundamentally different ways from the specialized herders considered here. Ultimately, the focus on a single obsidian quarry to supply a landscape of affiliated communities, when other contemporaneous groups were ignoring or denied access to that quarry, speaks to decisions being made based on social and cultural factors rather than energy efficiency. This is to say that, perhaps, the Elmenteitan Obsidian Quarry and related terrane present a scenario in which assumptions from human behavioral ecology cannot be easily applied.

The Elmenteitan Obsidian Quarry provides a number of useful controls that are rare for quarry sites, and which may make this dataset useful for testing models of lithic production. Now that there is a preliminary understanding of Elmenteitan quarrying and quantification of blade production strategies, it is possible to begin developing comparative analyses that test both the models for resource transportation presented by Brantingham (2003), Shott (2015) and others, and the social models for obsidian access and control posed for the Pastoral Neolithic of eastern Africa. Employing these models, even if they are refuted, will be immensely important in answering the questions posed for the Elmenteitan, and for the expansion of African herding in general.

Conclusions

Preference for obsidian from the Mt. Eburru obsidian sources over other lithic raw materials situates the Elmenteitan Obsidian Quarry site at the heart of a system of lithic extraction, distribution, production, and use that spans southwestern Kenya. Major questions about the social and economic structures of early pastoralism in the region are thus inexorably linked to the success of archaeological fieldwork and lithic analysis for this and other quarry sites. Here, I have attempted to establish a quantitative point-of-origin signature that can be used to better understand the movement of raw material between Elmenteitan herders across southern Kenya, and the variation in their technological strategies through time or across different regions and environments.

An attribute-based approach that assesses changes through a metrically defined reduction sequence, though coarse in some respects, presents a relatively rapid and efficient analytical strategy for accomplishing this goal. In and of itself, this dataset has limited potential to address the larger questions facing Pastoral Neolithic archaeology, and the conclusions I have reached remain largely speculative. The quarry study does demonstrate the viability of this type of approach for identifying meaningful dimensions of blade core morphologies in Pastoral Neolithic lithic industries that can be quantitatively measured and compared. In other words, the quarry study provides the necessary foundations for the next stage of regional comparative analysis in the region, which can address major questions.

Quarrying and raw material acquisition were important dimensions of hominid behavior throughout the evolution of our species (Ambro and Lorenz 1990; Foley and Lahr 2003; Minichillo 2006; Wilkins 2017), which persisted into the ethnographic present (Gallagher 1977). Different strategies of quarry use and raw material distribution may have been important components in processes in Africa like the origin of modern human behavior through to the spread of food production. Archaeological work at the Elmenteitan Obsidian Quarry confirms the potential, and indeed the importance, of quarry archaeology for research in Holocene African. The frequency of quarry sites used by diverse forager and food-producing groups in the Central Rift Valley offers unique opportunities to explore the connections between quarrying behaviors and broader economic and subsistence strategies (Ambro 2012; Brown et al. 2013; Merrick and Brown 1984). Further developing these models across time and space requires more attention to ancient lithic quarries and workshop sites, and their role in major processes like the development.

Quarries are often discussed as archaeological problems, but that framework is becoming increasingly disingenuous. It is clear that archaeological quarries are instead productive opportunities for addressing important anthropological
research questions. This case study may also be relevant for ongoing discussions of the role of quarries and quarrying debris within lithic technological analyses (Beck et al. 2002; Dillian 2007; McCoy et al. 2011; Messineo and Barros 2015; Mills et al. 2008; Shott 2015; Shott and Olson 2015). It emphasizes, if nothing else, that quarries are places of both economic and social (re-)production, and considerations beyond optimal foraging drive many aspects of raw material choice and quarry exploitation (Beck et al. 2002; McCoy et al. 2011; Purdy 1984; Taçon 2004). To truly appreciate the multifaceted datasets that quarry archaeology can produce, we must continue exploring new methodologies and techniques for extracting high-resolution data, which can be used to continue testing models and addressing questions of major anthropological importance.

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