Approaches for Understanding Flake Production in the African Acheulean

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ABSTRACT

Acheulean lithic technology is comprised of more than handaxes or other large cutting tools. Artifact assemblages from Member 11′ of the Olorgesailie Formation, Kenya, form the basis of our detailed examination of the flake and core component of an Acheulean behavioral system preserved in sediments dating to ~662–625 ka. We contrast what we consider descriptive and explanatory methods of lithic analysis currently in use among researchers studying the African Early Stone Age, and explore here an 'industry-free,' attribute-based analysis for the study of raw material economy. For sites from Member 11′ and Member 1 (~990 ka) of the Olorgesailie Formation, we compared the size of transported artifacts, the reduction intensity of flaked pieces, and flake utility (estimated by the ratio of flake cutting edge:thickness). Our results suggest a positive relationship between raw material economy and inferred paleoenvironmental structure, and demonstrate that the analysis of flakes and cores is an important complement to the study of handaxes, cleavers, and other characteristic Acheulean artifacts.

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INTRODUCTION

Much of the current debate on the relative merits of the *chaîne opératoire,* core reduction, and other approaches to understanding stone tool production has been shaped by analyses of Eurasian Paleolithic sites and assemblages. Data from Africa, particularly in areas distant from the Mediterranean, have often played a peripheral role. However, recent technological analyses of how Oldowan (e.g., Delagnes and Roche 2005; de la Torre 2004; Roche et al. 1999) and Middle Stone Age (e.g., Pleurdeau 2003; Tryon 2006; Van Peer 1998; Wurz 2002, 2003) hominins produced stone tools provide renewed impetus to assess how *chaîne opératoire*, quantitative, and other research approaches can elucidate the African archaeological record. Our interest in these issues arises from studies of eastern African Acheulean sites, where diverse researchers from different countries and intellectual traditions conduct research and employ varied typological, technological, or methodological frameworks (e.g., Clark 2001; McBrearty 2001; Potts 1994; Roche and Texier 1995; Toth 1985). Given the emphasis on flakes and flaked pieces in studies of Oldowan and Middle Stone Age sites, we focus here on comparable elements from Acheulean assemblages.

WHY STUDY FLAKES AND CORES IN THE ACHEULEAN?

The taxonomic process of naming artifact industries provides a shorthand that simplifies the diversity of the archaeological record. While by definition industries, industrial complexes, and other groupings encompass a range of artifact forms, in practice, novel or diagnostic elements are emphasized at the expense of artifact types that may have appeared earlier (although these may be more abundant), akin to the cladistic practice of classification according to derived rather than primitive traits (e.g., Foley and Lahr 2003). This is particularly evident for Acheulean sites, where research has focused primarily on the large cutting tools (e.g., handaxes, cleavers, and knives) rather than the flakes, cores, and smaller flaked pieces that numerically dominate most unwinnowed assemblages (e.g., Kleindienst 1961; Clark and Howell 1963; Leakey and Roe 1994).

We approach the Acheulean from a perspective that shifts the emphasis away from the meaning of the shape of the large cutting tools, studies of which have tended to dominate most discussions of this period (e.g., Gowlett and Crompton 1994; Lycett and Gowlett 2008; Lycett and von Cramon-Taubadel 2008; McPherron 2000; Noll and Petra-

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glia 2003; Sharon 2008; White 1998; Wynn 1995). We reason that the other elements of the Acheulean lithic toolkit, notably cores and flakes, may yield insights into the nature of hominin adaptation that may have been masked by studies of large cutting tools alone. Finally, understanding the flake and core component of the Acheulean is particularly important for studies of long-term temporal variation. After all, sites of the Oldowan and the Middle Stone Age (MSA) bracket those attributed to the Acheulean Industrial Complex. As many Oldowan and MSA sites are characterized by the production of sharp edged flakes or small tools on flakes, it may be that variation in flake and flake tool production through time is more relevant than the presence or absence of particular implement forms such as large cutting tools. Our objective is to obtain a measurement of variation through time without recourse to a potentially varied set of existing artifact typologies developed for specific periods or places, the use of which has created problems elsewhere, as in studies of the Middle-Upper Paleolithic transition in Eurasia (e.g., Brantingham et al. 2004; Grayson and Cole 1998). Although the traditional terminology is retained here for simplicity, our focus on cores and flakes effectively removes the need for higher order levels of archaeological taxonomy such as 'Oldowan,' 'Acheulean,' or 'Middle Stone Age;' it is 'industry-free' in much the same way that many studies of ecomorphology are, to a certain extent, 'taxon-free' (e.g., Plummer and Bishop 1994).

WHICH METHODOLOGICAL APPROACH TO USE?

Different philosophies of and approaches to lithic analysis can be applied in any given study, and our choice of methods was driven in part by the desire to produce results that could be interpreted within existing Early Stone Age analytical frameworks, but also to initiate more direct intra- and inter-site comparisons. Comparing artifact assemblages, whether at the scale of a single site or between different field study areas, is critical to answering many important archaeological questions, highlighting the value of exploring the extent to which different approaches are complementary. The goal of any comparative lithic analysis is thus to first describe and subsequently to explain observed differences.

The foundation of lithic analysis is a synthetic understanding of the particular means by which stone was knapped. Several recent reviews (e.g., Bleed 2001; Shott 2003) have highlighted the parallel development of this understanding among researchers in America, France, and elsewhere, suggesting a shared interest by prehistorians globally to understand the dynamic behavioral processes that resulted in the formation of the archaeological record. Elements of what have come to be termed *chaîne opératoire* and core reduction approaches, respectively championed largely by French and American researchers, provide comparable ways of understanding how stone tools were manufactured and used in the past. Both explicitly recognize that each artifact is the outcome of a behavioral continuum from raw material procurement to final discard, typically conceptualized as a number of potentially discrete stages, including for example, 'roughing out,' use, and resharpening (cf. Callahan 1979; Collins 1975; Conard and Adler 1997; Geneste 1985; Inizan et al. 1999; Pelegrin et al. 1988; Schiffer 1987; Shott 2003). Interpretation of archaeological data among practitioners of either *chaîne opératoire* or core reduction approaches is based on inferences drawn from direct observation of human actions and their consequences, either in ethnographic contexts or during the course of the experimental replication of particular artifact forms or technical features, such as platform type or shape (e.g. Pelcin 1997; Pelegrin 2000). Possible outcomes of such analyses are schematic diagrams or flow charts that present readily comprehensible summaries of the flaking process. Such an approach is inherently a normative portrayal of an assemblage that reduces emphasis on internal variability, in part for simplification and clarity.

A different approach, which we consider to be complementary, is to summarize lithic assemblages in terms of statistical means and variances through analysis of quantifiable attribute data. Integration of such analyses within the study of lithic reduction sequences has a long pedigree among American scholars (e.g., Sackett 1966; Shott 1994; Stahl and Dunn 1982). Furthermore, a number of researchers have shown that concepts grounded in the French tradition of the *chaîne opératoire* approach to lithic technology are amenable to quantification (e.g., Kuhn 1995; Tostevin 2003a, 2003b; Van Peer 1992). The strongest approaches are likely those that can combine both qualitative and quantitative methods. However, it is worth noting that direct comparisons of descriptive and quantitative analyses have shown that, in some cases, the results may be contradictory rather than complementary (Dibble 1995).

Analyses of metric data, rather than comparison of descriptive types, more readily allow for comparison among assemblages analyzed by different analysts provided that consistent or reliable procedures are established (e.g., Fish 1978; Odell 2003: 125–129; for discussions of inter-analyst variation, see Calogero 1992; Perpère 1986). Quantitative data may reveal characteristics of a particular assemblage that descriptive methods alone cannot. Of course, the converse may also be true, particularly for subtle differences in three-dimensional shape, although significant advances are being made in this direction (Clarkson et al. 2006; Lycett et al. 2006; Archer and Braun 2010). Quantitative methods are also particularly amenable to hypothetico-deductive approaches that rely upon statistical analyses. The latter point is particularly relevant to the context of this issue, and forces us to ask whether the contrast should be between different intellectual schools such as *chaîne opératoire* and core reduction, or whether it should be broader, and framed in terms of descriptive and explanatory approaches. Description alone is obviously insufficient to explain the causes of observed intra- or inter-assemblage variability in the means of stone tool production, and Bleed (2001: 123) notes the difficulties of evaluating the reasons why one particular *chaîne opératoire* or reduction mode was used over another. As described below, numerical analyses of spe-

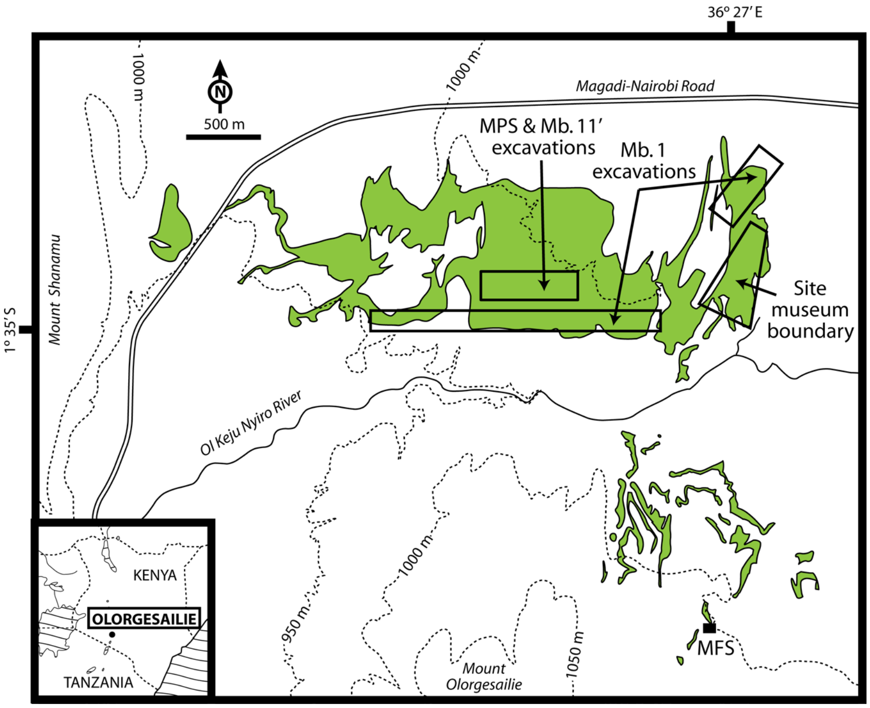

Figure 1. Schematic map of the Olorgesailie area showing the main exposures of the Olorgesailie Formation (shaded area), approximate areas of the Member 11′ and the Member 1 excavations (detailed in Potts et al. 1999), and locations of the Merrick Posnansky Site (MPS) and Mountain Foot Site (MFS)(after Shackleton [1978]).

cific attributes also can reveal important behavioral signals masked by typological or technological similarity, and enable the formulation and testing of questions about why, rather than how, hominins formed lithic assemblages in the ways they did. Such analyses have become common in evolutionary-ecological models that seek to explain behavioral variation in relation to environmental variables. Inherent within the goals of a *chaîne opératoire* approach is an understanding of the role of learned traditions in the geographic and temporal patterning of material culture (e.g., Inizan et al. 1999; Lemonnier 1992), and indeed, such questions are not unique to this method. However, French archaeology has a long tradition of attributing archaeological variability to hominin choice, stretching back from Boëda to Bordes to Breuil. This tendency is balanced by an equally strong American-based resistance toward ascribing variation to cultural choice until all other factors, particularly reactions to environmental stimuli, have been excluded, forming one of the central tensions in the current debate (Boëda 1991; Clark 1991; Isaac 1986; Sackett 1991).

Previous researchers have documented variation among Oldowan and Acheulean sites in the *chaînes opératoires* used in flake production (e.g., Roche et al. 1988, 1999; Roche and Texier 1995; see also Delagnes and Roche 2005). Our goal is to build upon this research by using an attribute-oriented approach to explore the causal factors underlying this variation. To do so, we turn to Acheulean lithic assemblages from the Olorgesailie Formation of Kenya where large cutting tools are sparse or absent.

THE OLORGESAILIE FORMATION OF KENYA: A TEST CASE

Located in the southern Kenya Rift Valley, the Olorgesailie basin contains sediments divided into two main geological units, the oldest of which is the Olorgesailie Formation, approximately 80m thick (Isaac 1978; Potts et al. 1999). The basin area is ~300km^2, and an abundance of archaeological remains is exposed near the northern base of Mt. Olorgesailie. This mountain and nearby volcanic ridges were critical sources of lithic raw material for Acheulean and later toolmakers who occupied the basin (Figure 1). Our focus here is on sites and sediments of the Olorgesailie Formation, where concentrations of typical Acheulean implements such as handaxes were first reported by Gregory (1921), and subsequently investigated by Leakey (1952), Posnansky (1959), Kleindienst (1961), and in detail by Isaac (1977). Potts (e.g., 1994; Potts et al. 1999) has conducted a program of paleolandscape investigations here since 1985. Results of this project include a precise chronological framework for the Olorgesailie Formation, which spans ~1200–490 ka, with detailed habitat reconstructions and artifact distributions for several intervals (see Behrensmeyer et al. 2002; Deino and Potts 1990; Potts et al. 1999; Sikes et al. 1999; Owen et al. 2008).

We describe our results as of 2006 of our ongoing analysis of artifacts (sample=3,509 specimens) from ten excavations directed by Potts in 1998–1999 in a narrow stratigraphic interval (~0 to 40cm thick) at the top of Member 11′ of the Olorgesailie Formation, the lowermost of three sub-members within Member 11 initially recognized by

Shackleton (1978) and Isaac (1978). This stratigraphic interval is defined by a laterally continuous, distributary sand that was deposited as lobes and sheetwash over a subaerially exposed diatomaceous lake flat. Bracketing Ar^{40}/Ar^{39}-dated tephra provide age estimates of ~662–625 ka for these Member 11′ sites, which comprise the youngest excavated series of sites in the Olorgesailie Formation. Although the Member 11′ excavations can be divided geographically from east to west over an outcrop length of about 1km, we group together all of the excavated material from this paleolandscape for the purpose of this analysis. In the target interval, the lateral distribution of artifacts was highly patchy, and included very dense clusters, on the one hand, and a very sparse background scatter, on the other, representing a degree of variation similar to that seen in handaxe-rich strata of Member 7 (Isaac 1977; Potts et al. 1999). All sites described here are broadly laterally equivalent to previously reported excavations by Posnansky (1959) at what subsequently became known as MPS (Merrick Posnansky Site) and at the Mountain Foot Site (MFS), as described by Isaac (1977).

Initial investigators (Leakey 1952; Posnansky 1959) noted the lack of handaxes or other large cutting tools from Member 11 sediments, something also true of the assemblages examined here, and attributed them to the Hope Fountain industry. Clark and Howell (1963; see also Clark 1953, 1959 and Binford 1972) subsequently subsumed the Hope Fountain industry into the flake and core component of the Acheulean industry (i.e., as the Acheulean without handaxes, cleavers, or knives), later renamed the Acheulean Industrial Complex (e.g., Clark 1994; Clark et al. 1966, 1994). Although Isaac (1977: 78), reports handaxes eroding from Member 11 sediments (the Mountain Foot Site), the nature of the material found in the recent excavations necessitated a focus on the non-large cutting tool portions of Acheulean assemblages, providing us with the opportunity to highlight the widespread nature of this under-researched component of Acheulean behavior. Our comparative reference for the Member 11′ artifacts is material from paleolandscape excavations in upper Member 1 of the Olorgesailie Formation, dated to ~990 ka (Potts et al. 1999), because the sample size is large and because of the use of identical analytical procedures when previously examined by Potts and Michael Noll.

ANALYTICAL METHODS

Our collaborative analysis of the Olorgesailie assemblages is the result of very different research traditions, experience, and personal perspectives. These differences derive in part 'from the Oldowan up' perspective of Potts and 'down from the Middle Stone Age' perspective of Tryon. Tryon's prior research and training has focused on the study of typological and technological shifts across what has been termed the 'Acheulean-Middle Stone Age transition' in eastern Africa, using, in part, a *chaîne opératoire* approach (e.g., Tryon 2005, 2006; Tryon and McBrearty 2006; Tryon et al. 2005). Potts has used attribute-based analyses to test for typological, technological, or distributional variations among Oldowan and Acheulean assemblages (Potts 1988, 1991; Yamei et al. 2000). From the beginning, these research differences led us to try to integrate descriptive and explanatory analyses of Acheulean lithic assemblages that reflect the diverse methods practiced by researchers in eastern Africa. However, our choice of analytical methods was based on our objective of comparing the Member 11′ artifact assemblages with those excavated in Member 1. In other words, previous analytical research at Olorgesailie by Isaac, Noll, and Potts—with its emphasis on quantitative attributes—played a critical role in establishing the basis for comparison and thus the approach we took toward the Member 11′ sites. In this paper, we attempt to make our current analytical procedures, goals, and future directions clear, and present our initial explorations of these ideas.

Analysis of Site Formation Processes

Our starting point is an understanding of the diverse processes affecting the composition of recovered lithic assemblages. The available data suggest that the Member 11′ artifact assemblages are the result of complex depositional and post-depositional histories. These are assessed using methods derived from field- and flume-based experiments examining the effects of different depositional processes on artifacts of varying sizes and weights, the results of which are now widely applied to Early Stone Age sites (for further details, see Petraglia and Potts, 1994; Schick, 1986, 1988). As a detailed analysis of site formation processes is beyond the scope of the present paper, we simply note for the Member 11′ sites: (1) the absence or rarity of elements < 1 cm in maximum dimension, despite sieving of all excavated sediment through 1-mm mesh; (2) the predominance of lithic fragments 2-3 cm in maximum dimension and that weigh > 50 g; and (3) the presence of pieces with some form of edge rounding. Alluvial processes that resulted in the winnowing of small elements and minimal artifact transport have affected all of the Olorgesailie Member 11′ sites. These are interpreted as lag rather than transported deposits, and as such, the individual sites reflect the location of hominin visitation and discard, and the patchiness of artifact distribution across the Member 11′ paleolandscape can therefore be attributed to hominin behavior, rather than to reworking by water or other post-depositional processes.

Typology and Technology

Basic artifact classification followed the nested hierarchical scheme elaborated by Isaac (1986; Isaac et al. 1997) for Plio-Pleistocene sites at Koobi Fora (Kenya), dividing lithic artifacts into flaked pieces, detached pieces, pounded pieces, and unmodified pieces. For flaked pieces, we employ a modified version of the typology developed by M.D. Leakey (1971) in her study of Olduvai Gorge, retaining her definitions if differing at times in interpretation (cf. Toth 1985). Despite initial reservations by Tryon, the Oldowan typology readily accommodated all observed forms of flaked, detached, and pounded pieces of stone collected and examined. Divergence from 'typical' forms described by Leakey are attributed to shape differences imposed by the frequent

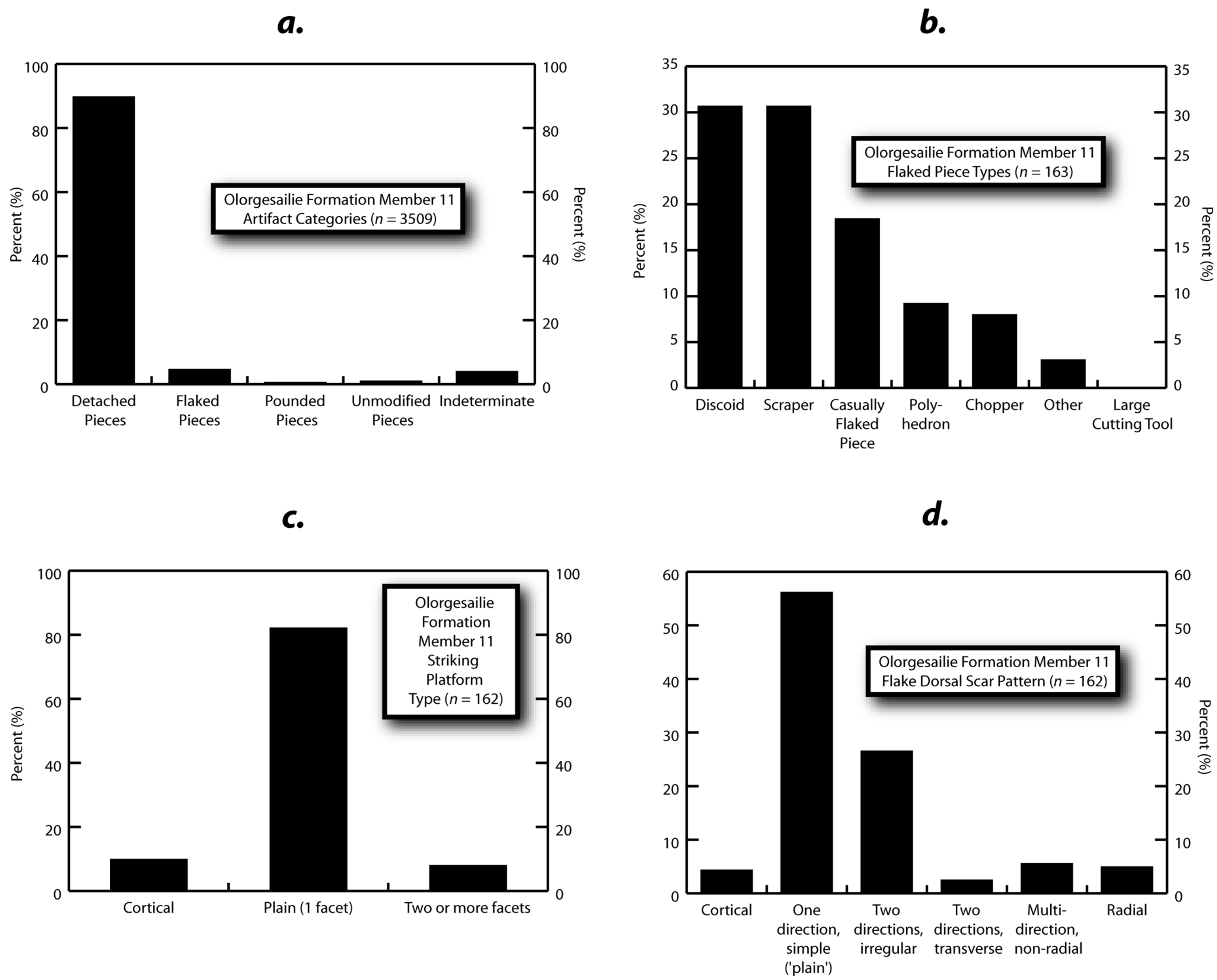

Figure 2. Relative abundances of Olorgesailie Member 11′ artifact assemblages discussed in this paper: a) major artifact classes; b) flaked pieces; c) striking platform type; and, d) flake dorsal scar pattern.

use by Olorgesailie hominins of slabs, spalls, and other angular fragments, rather than rounded cobbles, as initial raw material forms (Noll 2000). For example, choppers are defined by a single flaked edge characterized by an either uni- or bidirectional pattern of flake removals, regardless of initial form. Similarly, we view 'discoids' as typologically synonymous with the discoidal/centripetal/radial category of flaked pieces found throughout Paleolithic sites worldwide.

The typological compositions of the Member 11′ assemblages are summarized in Figure 2. With few exceptions, all are made of lavas locally available within the Olorgesailie basin, and all rock types found in the Member 11′ assemblages also occur in other, older assemblages of the Olorgesailie Formation. The general Oldowan character of a simple approach to the production of sharp-edged flakes implied by flaked piece typology is further accented by the dorsal scar patterns on complete flakes and striking platform types (see Figure 2), although recent refitting studies have shown that typological simplicity may mask technological complexity, at least as measured in terms of the number of flakes produced per core (Delagnes and Roche, 2005). We note that the relative size and shapes of the striking platforms observed on flakes and the presence of distinct impact cones on some specimens are consistent with direct hard hammer percussion (e.g., Crabtree 1982; Pelegrin 2000), further suggested by the presence of six battered cobbles with localized small pits that we interpret as probable hammerstones. Only a single flake is tentatively identified as a biface trimming flake, with distinct platform lipping that may also indicate use of an organic hammer, although the criteria for recognizing such flakes or attributes remain controversial (see Pelcin 1997). Several large flaked pieces were made on split cobble fragments, with at least two showing battering on opposed ends, suggesting percussion with the core held stationary against a harder substrate, a technique evident in Oldowan and Acheulean assemblages, and superficially similar to the nut-cracking procedures of an extant chimpanzee population (Jones 1994; Mercader et al. 2002; Toth 1997).

The non-handaxe components of the Olorgesailie Member 11′ lithic assemblages can be accommodated by the typological terms that also characterize Oldowan archaeological sites, despite the recent scrutiny many Oldowan or Acheulean lithic assemblages have received in the search for behavioral diversity (e.g., de la Torre 2004; de la Torre et al. 2003; Hovers and Braun 2009). Although more rigorous comparisons are required to test our current understanding, based upon our detailed inspection of numerous artifact assemblages as well as published descriptions and illustrations, there are no obvious typological or technological criteria that distinguish the Olorgesailie Member 11′ flakes and cores from those reported from Beds I and II Olduvai Gorge, older strata at Olorgesailie, or for that matter, many Middle or even Later Stone Age sites (Clark 1994; Clark et al. 1994; Gowlett 1999; Isaac 1977; McBrearty 2001; Noll 2000; Soriano 2003). Some discoids made on split cobbles bear a resemblance to 'Karari scrapers' from Koobi Fora (Harris and Isaac 1976; Ludwig and Harris 1998), an impression that merits further investigation. The need to move beyond description alone and to integrate the Member 11′ assemblages into a comparative context led us to explore additional analytical approaches, as described below.

DEVELOPING AN INTERPRETIVE FRAMEWORK

Having examined the basic typological and technological characteristics of the Member 11′ assemblages, we now examine it from the perspective of evolutionary ecology. In this regard, we assume that stone tools and tool assemblages reflect solutions to given problems within a broader foraging context as hominins pursued subsistence needs. We focus on lithic raw material economy and its role in shaping hominin technological strategies in relation to resource availability due to the archaeological visibility of stone artifacts. Our approach follows recent studies that use the concept of optimization in the analysis of lithic assemblages and habitat variability (e.g., Ambrose and Lorenz 1990; Bamforth 1986; Blumenschine et al. 2008; Bousman 1993; Braun et al. 2008; Kuhn 1995, 2004; Nelson 1991). In general, the movement of both modified and unmodified pieces of stone to areas away from raw material sources incurs potential transport costs in terms of time and effort. Transported stone represents a finite resource, as the manufacture and use of stone tools is a subtractive process that results in a decrease in the amount of usable stone. It is thus reasonable to assume that conservation of this finite and diminishing resource is beneficial; that is, there is an advantage to obtaining the maximum utility per unit of stone. The degree of this advantage will vary according to raw material quality and source distance, as well as the abundance and predictability (in space and time) of the resources or tasks for which the tools are to be used. When raw material constraints are held constant, environments characterized by unpredictable resources should be associated with an increase in economizing measures to insure that stone tools are available when and wherever they are needed, in comparison to environments with more abundant resources whose availability may be more readily and accurately anticipated.

Prior research in the Olorgesailie Formation has established the following baseline that our more recent work in Member 11′ builds upon.

1. *Raw material availability.* The depositional basin in which Olorgesailie Formation sediments accumulated lacked streams of sufficient competence for the transport of lithic clasts suitably sized for flake or tool production. Therefore, all artifacts were carried from local highland sources (Mt. Olorgesailie foothills and nearby ridges), with only a small percentage (<2% by number and weight) of the artifacts derived from more distant sources. All of the local sources represent Pliocene to early Pleistocene lavas, for which the location, outcrop extent, and past exposure or burial is now fairly well understood (Noll 2000; Potts 1994; Potts et al. 1999; Shackleton 1978). This situation provides a good case for examining raw material transport, and detailed efforts are underway to characterize the diversity of stone sources and artifact provenances. Furthermore, raw material quality is generally a key factor affecting assemblage composition (e.g., Andrefsky 1994), and the quality of various raw materials in the Olorgesailie area specifically has been assessed through knapping experiments and with more quantitative evaluations provided through a series of rock mechanics tests typically developed for engineers (Noll 2000).
2. *Paleoenvironment*. Reconstruction of the upper Member 1 and Member 6/7 paleoenvironments is detailed in Potts et al. (1999) and Sikes et al. (1999). Based on the presence of a widespread paleosol, stable carbon and oxygen isotope values of pedogenic carbonates, and a fossil fauna composed primarily of grazers, upper Member 1 is interpreted as a sparsely wooded grassland with artifacts continuously and slightly patchily distributed across the ancient landscape. Ongoing analyses by Potts, A.K. Behrensmeyer, and R.B. Owen (e.g., Owen et al. 2008) further indicate that the Member 1 artifacts accumulated during a lengthy interval of high aridity-moisture variability, resulting from climatic fluctuation, which suggests a period of overall resource unpredictability. The Member 6/7 paleolandscape, by contrast, is dominated by proximal floodplain sands adjacent to highly localized, shallow sand-filled channels that drain into a wetland. Artifacts in Member 6/7 occur in dense clusters within the channel features, with very low artifact densities in the interfluve zones between the channels (Potts et al. 1999). Although reconstruction of the Member 11′ paleolandscapes is still in progress (Tryon et al. 2009), a preliminary assessment suggests an overall similarity to that described for Member 6/7, which we use as our present model.

The fauna from our Member 11′ paleolandscape excavations indicates a open-vegetation habitat dominated by grazing bovids, while the combined fauna recovered in other strata of Members 10 through 11 indicate either a mixture of or an alternation between bushland and open grassland settings (Isaac 1977; Potts 2007). Both Members 6/7 and 11 were deposited during a prolonged period when predicted intervals of stability alternated with higher climatic variability. It is not yet possible to determine whether the thin stratigraphic unit in which the Member 11′ artifacts are found was deposited under conditions of stability or higher climate variability.

3. *Biface economization*. The shape of bifaces in general, and Acheulean handaxes in particular, have been argued to be the outcome of selective pressures favoring the maximization of cutting edge perimeter for the minimal amount of excess weight or volume (e.g., Jones 1994). Site-to-source data for a number of Acheulean sites demonstrate that handaxes and other large cutting tools were routinely (but not always) transported short distances, typically <10km (e.g., Feblot-Augustins 1990), and transport weight is an important limiting factor for any mobile foraging group of hominins. Noll (2000: 283–284; Noll and Petraglia 2003) links large cutting tool (e.g., handaxes, cleavers, and knives) reduction intensity to resource availability at Olorgesailie, hypothesizing that more intensively reduced large cutting tools (LCTs) from upper Member 1 than in Member 6/7 of the Olorgesailie Formation is a result of inter-member environmental contrasts. LCT reduction intensity is determined through comparisons of LCT size, edge angle, and flake scar counts (including stepped terminations). Noll (2000; Noll and Petraglia 2003) suggests that the Member 1 large cutting tools were discarded only after intensive flaking of pieces through repeated episodes of resharpening because of an open habitat that implies lower food density and less resource predictability. Conversely, Member 6/7 artifacts occurred in a relatively more closed and bushy habitat, which may imply higher rainfall and resource abundance. Under such conditions of increased predictability (suggested by the artifact distribution), pressures to conserve and economize artifacts may be relaxed, leading to discard of Member 6/7 large cutting tools before exhaustion.
4. *Flakes and cores*. It is clear that flakes and cores were typically moved across Pliocene and Pleistocene landscapes, as evidenced at Olorgesailie, other eastern African Acheulean localities such as Koobi Fora (Kenya), Isimila (Tanzania), Olduvai Gorge (Tanzania), and Kalambo Falls (Zambia), and in settings that record some of the oldest archaeological traces (e.g., Bouri, Ethiopia) (Bunn et al. 1980; Clark 2001; de Heinzelin et al. 1999; Howell et al. 1962; Isaac 1977; Leakey and Roe 1994; Potts 1994; Potts et al. 1999). Because flakes and cores were transported, they should be subject to similar pressures as large cutting tools to maximize utility while minimizing excess weight (e.g., Braun and Harris 2003; Braun et al. 2008; Kuhn 1994; Roth and Dibble 1998).

Noll's (2000) interpretations of raw material economy were based primarily on his study of large cutting tools from Olorgesailie. In this comparison, our aim is to test the hypothesis that other elements of Acheulean assemblage variability, particularly flakes and cores, are sensitive indicators of patterns of hominin economizing behavior linked to differences in resource availability. We predict that the Member 1 lithic assemblages should show greater evidence of economizing behavior than those of Member 11′, either through more extensive reduction prior to discard or in the manufacture and use of forms that maximize utility per unit weight or thickness. Our measure and interpretation of observed differences are based on the concept of optimization (for recent reviews of its application to ethnographic and archaeological populations of foragers, see Bettinger 1991; Bird and O'Connell 2006; Kelly 1995; Winterhalder 2001), predicting that adaptive pressures will favor behaviors and resultant artifact forms that maximize utility while minimizing excess weight or size (e.g., Beck et al. 2002; Braun 2005; Brantingam and Kuhn 2001; Kuhn 1994).

Unless otherwise noted, pairwise differences are assessed using t-tests at the 95% confidence interval. We test for differences between Member 1 and Member 11′ in: 1) the extent of raw material reduction prior to discard in terms of the weight of unmodified and flaked pieces, as well as the degree to which core perimeters were flaked, measured as the proportion of flaked-edge length of a piece relative to its total circumference (measured using a string held to the edge of the piece); and, 2) we also compare the shape of the flakes produced, measured in terms of effective cutting edge to weight and flake thickness (e.g., Kuhn 1994; Roth and Dibble 1998), a relative measure originally introduced by Leroi-Gourhan (1964), among the foremost founders of the *chaîne opératoire* approach (see Lemonnier 1976; Inizan et al. 1999: 13–17). Cutting edge was estimated by flake area (flake length x width, following Isaac [1977]). In this case, thickness is likely a more reliable indicator than weight due to the variable densities of the lithic raw materials studied here (Noll 2000). Thinner flakes have greater amounts of cutting edge than do thicker flakes with the same surface area, and thus minimize the amount of transported stone that is unusable. Strategic production of thinner flakes also serves to prolong the life of a given core, as each flake removes a smaller portion of the core compared to thicker flakes. Exploratory analyses were also conducted to examine the extent of at-source vs. on-site flaking, measured by the amount of flakes that retain cortex, which we consider to be suggestive of earlier stages of reduction. This provides a further behavioral context in which to interpret

TABLE 1. COMPARISON OF MEMBER 1 AND MEMBER 11' ATTRIBUTE DATA.[a]

	Member 1		Member 11'		Statistical comparison		
Variable	**n**	**mean ± s.d.**	**n**	**mean ± s.d.**	**t**	**d.f.**	**p**
Weight (g) of unmodified pieces	243	376.4 ± 558.8	35	386.7 ± 328.3	-0.106	276	0.916
Weight (g) of flaked pieces	525	152.1 ± 267.0	135	143.4 ± 165.2	0.362	658	0.717
Flaked piece edge length: circumference	382	0.71 ± 0.32	131	0.62 ± 0.32	2.948	511	0.003*
Flake area : weight (mm²/g)	2568	168.3 ± 132.1	179	90.3 ± 49.8	7.864	2745	0.000*
Flake area : thickness (mm)	2570	68.7 ± 47.6	180	95.8 ± 48.7	-7.380	2748	0.000*

[a]Note that flake area was measured only for complete flakes, a subset of the detached piece category; see text for further definition of variables and their measurement. For each variable, the number, mean, and standard deviation are provided. Results of t-tests include t value, degrees of freedom, and probability, with results significant at or above the 0.05 level marked with an asterisk.

inter-member differences in the use and transport of stone resources at Olorgesailie.

RESULTS

Although similar amounts (by weight) of unmodified and flaked pieces were deposited across the two excavated sampling areas of Member 11′ and Member 1 (Table 1, lines 1 and 2), the Member 1 flaked pieces (here, excluding large cutting tools) were more extensively reduced, as shown by significantly higher average ratios of flaked edge length to circumference (see Table 1, line 3). In the Member 1 sample, on average, ~71% of the circumference of the flaked pieces was modified, whereas the value for the Member 11′ sample was ~62%. These differences are consistent with greater reduction intensity (e.g., Potts 1991), and conform to expectations for more intensive use of lithic materials in Member 1. Flakes produced from the cores in Member 1 have a significantly greater flake area:thickness ratio and flake area:mass ratio than those from Member 11′; that is, on average, for the same amount of cutting edge, Member 1 flakes are thinner and lighter than those from Member 11′ (see Table 1, lines 4 and 5). These results conform to our expectations of greater economizing behavior where resources are scarce or unpredictable (in Member 1), following our present reconstructions of the Member 1 and Member 11′ paleoenvironments.

The proportion of cortical flakes suggests that the Member 11′ sites record a greater frequency of on-site knapping of minimally modified transported pieces. A total of 23.7% of the 3,289 complete flakes from Member 1 preserve cortex; in Member 11′ this value is 37.2% of 180 complete flakes. These differences are significant (X^2=8.56, d.f.=1, p<0.01), suggesting preservation of a larger proportion of flakes indicative of early stages of reduction, and thus the regular transport of minimally modified sources of raw material from nearby highland outcrops to the lowland basin during the formation of the Member 11′ sites. It remains to be determined to what extent this difference is related to variations in the types of stone used and differences in the initial form of the exploited raw material (e.g., as cobbles rather than angular fragments), with initial form likely having a marked effect on cortical abundance within an assemblage (Dibble et al. 2005). Alternatively, the comparative rarity of cortical elements among the Member 1 sites may indicate greater spatial fragmentation of the reduction sequence in the Member 1 assemblages, with a single core transported and flaked at various places on the landscape, resulting in no single location with high densities of cortical pieces, a hypothesis potentially testable through an extensive refitting program (e.g., Bunn et al. 1980; Cahen 1987; Hallos 2005).

SYNTHESIS

Artifact assemblages from Member 1 of the Olorgesailie Formation show more extensively worked flaked pieces and the manufacture of flakes with greater surface area:thickness ratios relative to those from Member 11′. We interpret these differences to reflect selective pressures to economize stone where resources are relatively sparse or unpredictable, as suggested by site distribution and paleoenvironmental reconstruction. Greater frequencies of cortex-bearing flakes among the Member 11′ assemblages suggest the import of minimally modified packages of raw material to the Olorgesailie lowlands, with more primary reduction (i.e., decortication) occurring at Member 11′ sites than those from Member 1. This difference may relate to still unexplored differences in raw material type and form, but is consistent with reduced pressure during Member 11′ times to transport material with the maximum amount of potentially usable volume; that is, pieces with cortex and other surface irregularities removed prior to transport.

FUTURE DIRECTIONS AND CONCLUSIONS

If, in fact, Member 1 and Member 11′ assemblages from Olorgesailie reflect a single system of raw material transport and core reduction to produce sharp-edged flakes, then the variability between Member 1 and Member 11′ reflects differences in the extent to which transported stone was flaked and the relative shapes of the detached pieces. For the present we consider both the Member 1 and Member 11′ assemblages to be part of an Acheulean behavioral system, but note a typological distinction with the absence of large cutting tools from the Member 11′ assemblages studied here (although found on the surface at the Mountain

Foot Site apparently eroded from Member 11 sediments), and their rare presence in some Member 1 excavations. One avenue for future research is to understand the degree to which this typological difference drives some of the attribute differences we have observed. Are the (on average) thinner flakes from Member 1 the result of biface thinning? Biface thinning flakes have been experimentally shown to have higher surface area:mass ratios (e.g., Prasciunas 2007; Tactikos 2003). Thus, did Acheulean handaxes serve as transportable multifunctional tools and as sources of flakes among mobile foraging populations (e.g., Kelly 1988) in places or during times of relative resource unpredictability and thus contribute indirectly to variation in relative flake size? Ongoing integration of the Member 6/7 comparative data will provide an important way to address this question as these strata include assemblages with variable abundances of handaxes, cleavers, and biface-thinning flakes in a reconstructed depositional environment similar to that of Member 11′ (Isaac 1977; Potts et al. 1999).

The structure of the paleoenvironmental record also needs to be considered. Our preliminary reconstructions suggest that resource stability, likely shaped by climate and vegetation, played a role in hominin investment in stone transport, curation, and reduction. However, landscape stability also plays a role in determining rates of artifact burial; stable landscapes such as that suggested by the Member 1 paleosol provide increased opportunities for artifact recycling, a process which may mimic reduction intensity. By contrast, many of the Member 11′ sites were likely rapidly buried in a fault-bounded accommodation zone during a period of landscape instability due to tectonic activity (Behrensmeyer et al. 2002; Potts et al. 1999), rendering prior artifact accumulations invisible to later site occupants. In addition to a complete analysis of all Member 11′ artifacts (Tryon et al., 2009), a further challenge is the integration of the results and analytical procedures presented here in a comparison with younger Acheulean or Middle Stone Age sites from the Olorgesailie basin (Brooks et al. 2007). This will provide an 'industry-free' method of examining archaeological changes in the African record that begin ~300 ka ('the Acheulean – Middle Stone Age transition'; see McBrearty and Tryon 2006). The reasons for this behavioral change remain unclear, but are significant given the association of the oldest remains of *Homo sapiens* in Africa with MSA artifacts in the Omo Kibish region of Ethiopia at ~195 ka (McDougall et al. 2005), and attendant uncertainties of first and last appearance datums for both fossil species and artifact types. Species-specific behavioral innovations, population pressure, and increased mobility as a means of adapting to climate variability have all been implicated (Henshilwood and Marean 2003; McBrearty and Brooks 2000; Potts 1998). Investigation of the latter hypothesis follows from our present preliminary investigations into the effects of paleoenvironmental variability on hominin behavior.

One of the goals of our future research is therefore to explore the hypothesis that many of the technical innovations that characterize the later Middle Pleistocene reflect the adoption of methods designed to increase artifact portability suitable for highly mobile populations facing habitat unpredictability. These include the use of organic or soft hammers in the production of bifaces, a technique at least as old as ~700 ka, as experimental evidence suggests that this technique allows for the production of thinner bifaces, thereby reducing volume (Hayden and Hutchings 1989; Texier 1996). Some later Acheulean sites (~400 ka) also are characterized by the production of large (>10cm) Levallois flakes for transformation into handaxes, cleavers, or comparable tools, as well as blade manufacture (McBrearty 2001; Texier 1996; Tryon et al. 2005). Levallois flakes, and blades in particular, have been argued to be blank forms that maximize cutting edge length while minimizing weight (e.g., Brantingham and Kuhn 2001). Testing this hypothesis will ultimately require a technologically grounded descriptive approach to identify what these changes are and when they appear, coupled with explicit testing of the results in a cost:benefit analysis from the perspective of mobility.

Our initial investigation of lithic assemblages from Member 11′ of the Olorgesailie Formation has sought to understand and explain some of the factors driving variability in the flake and core component of eastern African Acheulean sites. The project is the outcome of collaborative research that attempts to synthesize different approaches to stone tools and their manufacturing byproducts. We have sought to find a way that can combine both descriptive and explanatory measures of hominin flaking strategies. We employed an 'industry-free' approach, using the concept of optimization to study raw material economy among the 'non-handaxe' (or non-large cutting tool) elements of Acheulean lithic assemblages. Because our initial comparison of the Member 1 and Member 11′ material has revealed few obvious typological or technological differences, we have chosen here to interpret the observed variation in the archaeological record as the aggregate decisions of hominins in response to economic, rather than cultural constraints. In the end, the Acheulean is about more than just handaxes, and we hope to have demonstrated that substantial information about behavior may yet be extracted from other elements of the toolkit.

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