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Technological variation in the earliest Oldowan from Gona, Afar, Ethiopia

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ABSTRACT

Inter-site technological variation in the archaeological record is one of the richest potential sources of information about Plio-Pleistocene hominid behavior and evolution. However, appropriate methods for describing and comparing Oldowan assemblages have yet to be agreed upon, and interpretation of the early record remains highly controversial. Particularly salient is disagreement over whether the Oldowan is a single technological phenomenon or is more accurately divided into multiple regional and/or chronological traditions, perhaps including a less developed Pre-Oldowan phase in the late Pliocene. Some of this disagreement reflects theoretical and methodological differences between research traditions and some is more directly evidential. Here we present a framework for describing and interpreting Oldowan variation and apply it to three Pliocene assemblages (EG-10, EG-12, and OGS-7) from Gona, all dated to c. 2.6 million years (Ma). Results indicate proficient knapping and a full range of Oldowan reduction strategies in these earliest known occurrences, consistent with the idea of an Oldowan "technological stasis" from 2.6–1.6 Ma. Patterns of variation in raw material selection and predominant reduction strategy at each site clearly indicate the importance of cultural transmission in the Oldowan, but confounding ecological and economic variation continue to render interpretation in terms of multiple tool making traditions or species inappropriate. We propose that cultural transmission and ecological adaptation should be recognized as complementary, rather than mutually exclusive, mechanisms in future attempts to explain Oldowan technological variation.

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Introduction

The nature of technological variation in the Oldowan Industrial Complex (Isaac, 1976) has long been controversial (e.g., Leakey, 1971; Stiles, 1979; Toth, 1985; Roche, 1989; Kibunjia, 1994; Semaw et al., 1997; Ludwig and Harris, 1998; Kimura, 2002; Braun et al., 2005; Delagnes and Roche, 2005). This is an issue of enduring interest for Early Stone Age (ESA) archaeology because, together with paleontological, zooarchaeological, and paleoenvironmental evidence (Schick and Toth, 2006; Plummer, 2004), interassemblage technological variation is a key source for reconstructing early hominid behavior and evolution. Current interpretations range from the identification of a single, coherent "Oldowan" technological phenomenon spanning the entire period from 2.6–1.6 Ma (Semaw et al., 1997; Semaw, 2006) to the view that new archaeological taxa are needed to accommodate diachronic (Piperno, 1989; Roche, 1989; Kibunjia, 1994) and/or synchronic (Delagnes and Roche, 2005) variation during this period. These divergent interpretations are informed by empirical evidence but also reflect underlying theoretical and methodological differences between two broad research traditions in ESA archaeology (de la Torre and Mora, 2009).

Here we present technological analyses of three late Pliocene (2.6–2.5 Ma) lithic assemblages from the sites of East Gona (EG) 10 and 12, and Ounda Gona South (OGS) 7 in the Gona Research Project study area of Ethiopia (Fig. 1). These sites, along with several others from the Gona study area, are currently the oldest known in the world and have a central place in debates about the nature of Oldowan variation. In analyzing and interpreting these assemblages, we have attempted to integrate methods and theory from different research traditions to provide a more comprehensive perspective. Results indicate the presence of a stable range of variation (i.e., a technological stasis [Semaw et al., 1997; Semaw, 2006]) throughout the Oldowan time period but also identify

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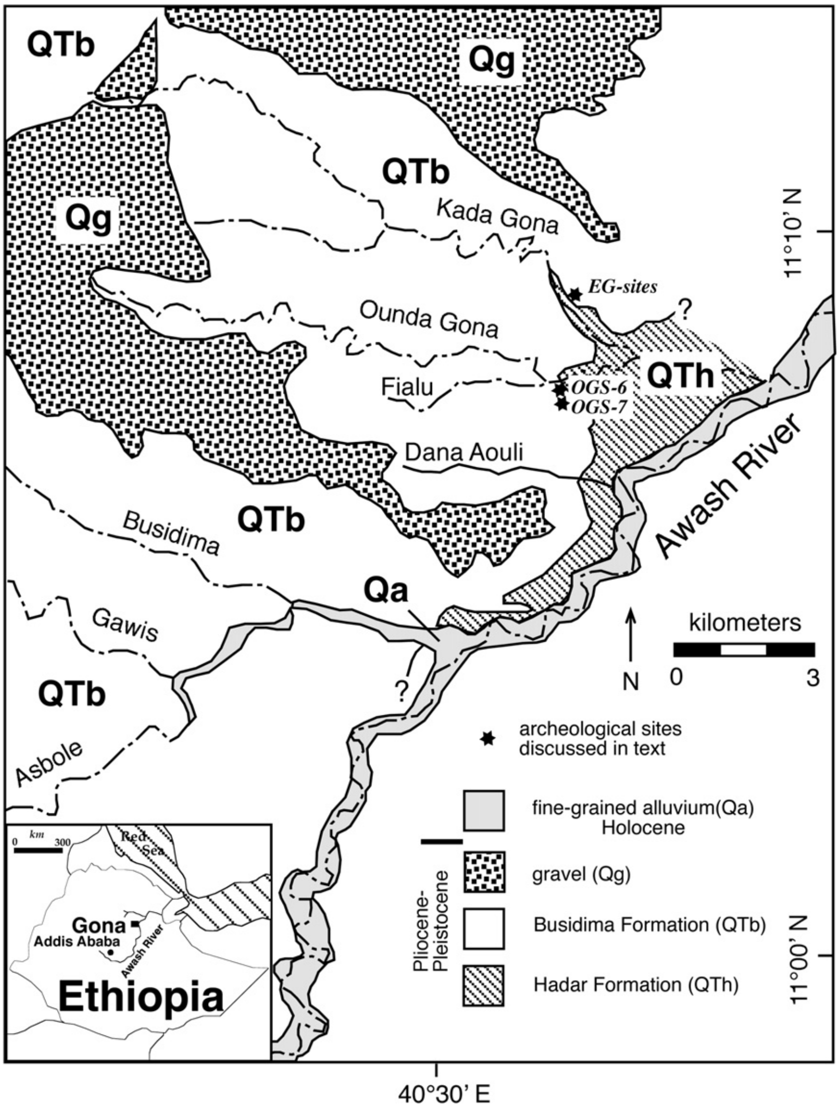

Fig. 1. The Gona Paleoanthropological Research Project study area.

important interassemblage differences in raw material selection and reduction methods that exist within this range.

Two approaches to Early Stone Age research

As recently reviewed by de la Torre and Mora (2009), two major theoretical approaches currently dominate ESA archaeology: a behavioral ecological approach largely derived from the work of Glynn Isaac (1984, 1986) and a "lithic reading" (Pelegrin, 2005) approach with its roots in the *chaîne opératoire* concept derived from Mauss (1936) and Leroi-Gourhan (1993). The behavioral ecological approach is characterized (e.g., Braun and Harris, 2003; Blumenschine et al., 2008) by its quantitative methods and theoretical emphasis on ultimate ecological and adaptive explanations of hominid behavior rather than on more proximate cognitive or social mechanisms. This approach takes cultural uniformity between assemblages as its null hypothesis, to be rejected only upon rigorous demonstration of differences that cannot be explained in any other way (Isaac, 1986). It is generally associated with treatment of the Oldowan as a unitary technological phenomenon, variable in its realization but uniformly centered on the least-effort production of sharp edges. This stable range of Oldowan variation has been described as a technological stasis (Semaw et al., 1997; Semaw, 2000) extending from the earliest known archaeological occurrences to the appearance of Acheulian Large Cutting Tools and more elaborate Mode I reduction strategies (Harris, 1978; de la Torre et al., 2003) c. 1.6 Ma.

This is in stark contrast to the lithic reading approach (e.g., de la Torre et al., 2003; Delagnes and Roche, 2005), which is characterized by its interpretive and qualitative methods and tendency to explain technological variation in terms of proximate mechanisms like hominid skill, conceptualization, and intention rather than more distal environmental or functional influences. In practice, this approach is often associated with the perception of greater diversity and complexity in the Oldowan, which has been seen to include intentionally shaped core forms (Texier and Roche, 1995; Delagnes and Roche, 2005), systematic reduction strategies (de la Torre et al., 2003), and clear cultural and/or chronological variants (Roche, 1989; Kibunjia, 1994). This has led some to further suggest that such variants may reflect the knapping activities of different hominid species (Kibunjia, 1990; Roche et al., 1999; Delagnes and Roche, 2005). These interpretations reflect an underlying assumption that techno-cultural diversity is more likely than uniformity across the vast spatio-temporal range of the Oldowan (Delagnes

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and Roche, 2005: 469), resulting in a null hypothesis exactly opposite to that of the behavioral ecological tradition.

These two research traditions have differing strengths, weaknesses, and biases that are reflected in divergent interpretations of the early archaeological record. In its more trenchant forms, for example, behavioral ecology is founded on the assumption that adaptive responses (i.e., behavioral phenotypes) are not substantially constrained by genetic, phylogenetic, and cognitive mechanisms (Winterhalder and Smith, 2000). This can be useful for the generation of testable predictions about early hominid behavior (e.g., Braun and Harris, 2003; Blumenschine et al., 2008), although behavioral ecologists themselves are increasingly aware of the limitations of such a simplifying "phenotypic gambit" (Grafen, 1984). Even the most ecologically-minded ESA archaeologists would likely agree that understanding the cultural and cognitive mechanisms underlying early hominid adaptations should be one of the ultimate goals of the field.

"Lithic reading," on the other hand, prioritizes cultural and cognitive explanations and places its emphasis on "deciphering" the intentions of the knapper (Inizan et al., 1999). This has an advantage in encouraging the kind of detailed behavioral reconstruction needed to study individual cognition and cultural transmission. However, there remains the danger that too great an emphasis on decoding intention might lead to the perception of design and intent in cases where evidence for these is lacking. Disagreements over interpretation can also be problematic as lithic reading is based on the technological expertise of the individual analyst (Pelegrin, 2005) and explicitly eschews the kind of controlled experimentation (Inizan et al., 1999: 96–7) and quantification that might provide a common ground for comparison and argumentation.

It is easy to view these two approaches as opposing one another, and indeed they are associated with conflicting interpretations of the early archaeological record. However, there are also important ways in which they may be complementary (de la Torre and Mora, 2009). One important area of overlap is the study of Oldowan knapping skill (Ludwig and Harris, 1998; Semaw, 2000; de la Torre, 2004; Delagnes and Roche, 2005; Stout and Semaw, 2006; Toth et al., 2006), which can clearly benefit from the "reading" of reduction sequences as well as from quantitative analyses of artifact attributes and ecological/economic context. Skill is of special interest because it reflects socially-reproduced behavioral competences acquired through deliberate practice (Isaac, 1986; Bril et al., 2005; Stout et al., 2005) and is thus relevant to discussions of ecological efficiency and adaptation (e.g., Braun and Harris, 2003) as well as to inferences regarding culture and cognition (Toth, 1991; Stout, 2002; Rossano, 2003; Stout and Chaminade, 2007; Stout, 2008). Researchers in both traditions recognize knapping skill as a reflection of sensorimotor, cognitive, and cultural capabilities (Isaac, 1986; Leroi-Gourhan, 1993), and see variation in its expression as an important indicator of potential cultural and/or biological differences between toolmaking groups. Unfortunately, there has been no agreement on specific criteria and standards that should be used to evaluate such variation. It is clear to us that a combination of theory and methods from behavioral ecological and lithic reading approaches will be needed to adequately address the question.

Late Pliocene technological variation

In recent years, the few known late Pliocene sites have become central to debates over Oldowan variation. These include Fejej (de Lumley et al., 2004), Gona (Semaw, 2006), Hadar (Kimbel et al., 1996; Goldman-Neuman and Hovers, 2009), Kanjera South (Braun et al., 2008a, 2009), Lokalalei (Delagnes and Roche, 2005; Harmand, 2009), and Omo (Chavaillon, 1976; Merrick and Merrick, 1976; de la Torre, 2004). Although it has often been argued that knapping at early sites was relatively crude (Chavaillon, 1976; Roche, 1989; Kibunjia, 1994), more recent technological analyses have consistently attributed a high level of skill to these assemblages (Ludwig and Harris, 1998; Semaw, 2000; de la Torre, 2004; Delagnes and Roche, 2005; Toth et al., 2006; Braun et al., 2009). This has led some proponents to abandon the idea of "continuous technological improvements" from a less elaborate pre-Oldowan phase (Delagnes and Roche, 2005: 496). The Gona sites of EG-10, EG-12, and OGS-7 are particularly important in this respect, as they provide evidence of competent knapping (Semaw, 2006) and selective raw material procurement (Stout et al., 2005) already in the earliest known archaeological occurrences.

Following the reassessment of Omo 57, 71, 84, and 123 (de la Torre, 2004), the only remaining candidates for less proficient knapping in the Pliocene are the Omo FtJi sites (Merrick and Merrick, 1976), which have yet to be re-examined, and Lokalalei 1 in West Turkana, Kenya. Lokalalei 1 has been described as opportunistic with a high incidence of edge battering and knapping accidents indicative of poor manual dexterity (Kibunjia, 1994; Delagnes and Roche, 2005). Although previously seen as part of a widespread pre-Oldowan phase of primitive knapping predating 2.0 Ma, evidence of skillful knapping at other Pliocene sites has now led to the alternative suggestion that the Lokalalei 1 toolmakers belonged to a different contemporaneous hominid species and/or techno-cultural tradition (Delagnes and Roche, 2005). However, as the researchers themselves note, "other factors, environmental or task related, cannot be ruled out" in explaining the "more expedient character of the Lokalalei 1 assemblage" (p. 468). A similar point regarding Lokalalei 1 has been made by others (Schick and Toth, 2006; Semaw, 2006; Harmand, 2009), and echoes comments made by Merrick and Merrick (1976: 580) in describing the Omo FtJi sites. Pending further research at Lokalalei 1, Omo, and elsewhere, there does not seem to be any compelling evidence for the existence of a less technically skilled variant of the Oldowan in the late Pliocene. However, the question remains as to whether inter-site differences in knapping methods (reduction strategies) may yet reveal an important dimension of variability.

The predominance of unifacial reduction at EG-10 and EG-12 has been well reported (Schick and Toth, 2006; Semaw, 2000, 2006; Toth et al., 2006). Combined with reports of predominantly unifacial flaking at Lokalalei 2C (Delagnes and Roche, 2005), Fejej (de Lumley et al., 2004), and Omo (de la Torre, 2004), this suggests the hypothesis that late Pliocene toolmaking was dominated by expedient unifacial reduction with a lack of core rotation and rejuvenation (e.g., de la Torre, 2004). This would be in contrast to high frequencies of bifacial reduction seen at many Pleistocene Oldowan sites (e.g., Toth, 1997; de la Torre and Mora, 2005), as well as the more systematic reduction strategies known from Mode 1 (Clark, 1977) assemblages contemporaneous with the early Acheulian (Harris, 1978; de la Torre et al., 2003). Delagnes and Roche (2005: 467) suggest that this difference might reflect limitations of at least some Pliocene toolmakers who "had the cognitive abilities to exploit angles when encountered but not to create new ones." According to Roche (2005), it was only with the "next stage of technological development" in the early Pleistocene that hominids became capable of creating advantageous core angles and morphologies, as indicated by the appearance of polyhedrons and spheroids after c. 1.9 Ma.

On the other hand, Delagnes and Roche (2005: 468) refer to evidence of polyhedrons from East Gona and Kanjera South in order to argue that the late Pliocene was more technologically complex and diverse than previously (e.g., Roche, 1989) contended. This would be consistent with Semaw's (2000; Semaw et al., 1997)

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assignment of the East Gona assemblages to the "classic" Oldowan (*sensu* Leakey, 1971), as opposed to a simpler "pre-Oldowan" industry (*contra* de Lumley, 2006). Cores from the c. 2.0 Ma site of Kanjera South similarly display a variety of reduction strategies, including alternating bifacial flaking, core rotation, and platform rejuvenation, consistent with assignment to the "Oldowan technological system"(Braun et al., 2009). Finally, recent work at the 2.6 Ma site of OGS-7 has identified a high proportion of bifacial flaking (Semaw et al., 2003) comparable to that seen in Pleistocene Oldowan sites. This calls into question the hypothesis that the earliest Oldowan tool makers were restricted in their selection of reduction strategies. Evidence from the Gona sites EG-10, EG-12, and OGS-7 is thus of central importance to discussions of Pliocene technological variation, and for this reason a more detailed comparative study of these assemblages is presented here.

Site context

EG-10 and EG-12 (Semaw, 1997) were discovered and excavated during the first systematic and extensive field studies at Gona, undertaken from 1992–94. The sites are located on the eastern side of the ephemeral Kada Gona River, approximately 7 km from the confluence with the perennial Awash River, and have been securely dated to between 2.6–2.5 Ma (Semaw et al., 1997). The artifact-bearing horizons occur in bedded silts of the second fining upward sequence above the base of the Busidima Formation (Quade et al., 2004), indicating a proximal floodplain context for site formation. Conglomerates composed of well-rounded cobbles up to 25 cm in diameter were deposited by the ancestral Awash River and form the base of the characteristic fining upward cycles of the Busidima Formation, followed by rhyzolith-rich sands, bedded silts, and capping paleo-vertisols. The Intermediate Cobble Conglomerate (ICC), which is prominently exposed just below EG-10 and EG-12, forms the base of the second sequence and was the closest source of the lithic raw materials used for making the East Gona stone artifacts.

At EG-10, stone artifacts were recovered from a 13 m^2 excavation and occurred in two discrete ~10 cm thick levels separated by 40 cm of sterile sediment. The artifacts were recovered from vertisolic clays with well-developed slickensides and aligned clay fabrics, consistent with a seasonal shrink-swell cycle that may have contributed to a certain degree of vertical dispersion and artifact fragmentation. Nevertheless, identifiable levels were preserved and artifact surfaces and edges remained remarkably fresh. EG-12 is located approximately 300 m north of EG-10, on a steep erosional slope incised by an ephemeral tributary to the Kada Gona River. Excavation of 9 m^2 exposed a single, 40 cm thick artifact horizon in well-consolidated brown blocky clay. As at EG-10, this vertisolic clay may have produced some vertical dispersion of artifacts, but surfaces and edges remain fresh.

OGS-7 (Semaw et al., 2003) was discovered and excavated in 2000. The site is located on a very steep slope above the Fialu, an ephemeral stream feeding the Ounda Gona River approximately 3 km SSW of EG-10 and EG-12. As at East Gona, the artifacts occur in the middle of the second fining upward sequence above the disconformity (~2.9 Ma) that marks the base of the Busidima Formation. The site is located 7.6 m below the Gonash-14 tuff (2.53 ± 0.15 Ma) and securely dated to 2.58 Ma by a combination of radiometric and paleomagnetic evidence (Semaw et al., 2003). Excavations at OGS-7 have been limited to 2.6 m^2 by the steep slope and >10 m of overburden; however, a large number of artifacts and some associated bone fragments have been recovered. Artifacts are tightly restricted to a <10 cm-thick layer and rest flatly along the sharp, slightly wavy contact between coarse sand below and bedded silts above. This implies a channel bank or margin context for site formation. Evidence of bioturbation or other disturbance is limited to a few isolated burrows and root traces (Quade et al., 2004). Twenty meters to the east of OGS-7 the sand laps onto a coarse conglomerate, which was most likely the nearest source for lithic raw materials.

Interpreting variation at Gona: theory

Behavioral ecological and lithic reading approaches both identify knapping skills as key indicators of hominid culture and cognition. But how are skills to be measured and compared? When should variation be attributed to biological differences between hominid species as opposed to cultural or economic variation? If variation is clearly related to environment, does this mean that it cannot also be indicative of biological or cultural differences? What should be the null hypothesis regarding cultural uniformity vs. diversity in the Oldowan? We believe that a combination of theoretical insights from the study of animal cultures and empirical evidence from experimental stone knapping studies may be helpful in addressing these difficult questions.

Biological variation

The identification of different species from behavioral evidence alone is inherently problematic. Different populations of the same species often display different behaviors, whereas different species sometimes display the same behaviors. For example, grooming handclasps and leaf-clipping are used as social signals by some, but not all, populations of both chimpanzees and bonobos (Byrne, 2007). The strongest case for biological differences among Pliocene toolmakers would come from clear differences in the underlying physical or cognitive requirements of technological variants. In the context of Mode I technologies, such differences might include sensorimotor capacities for efficient bimanual percussion and three-dimensional shape perception (Byrne, 2004; Bril and Roux, 2005; Stout and Chaminade, 2007) or cognitive capacities for complex action planning (Stout et al., 2008).

In principle, sensorimotor capacities can be inferred from various indicators of effective knapping technique (Stout, 2002; Stout and Semaw, 2006; Toth et al., 2006; Stout and Chaminade, 2007). Complexity of action planning, on the other hand, may be assessed through the detailed consideration of knapping strategies (de la Torre et al., 2003; Delagnes and Roche, 2005) and raw material economy (Stout et al., 2005; Harmand, 2009; Braun et al., 2009; Goldman-Neuman and Hovers, 2009). Unfortunately, patterns of technological performance observed at particular sites cannot be assumed to reflect the full range of species-typical capacities of the makers. It is always necessary to consider the potential influence of ecological context (e.g., tool function, raw material quality), cultural variation (e.g., preferred reduction strategies), and site formation processes (e.g., hominid transport, fluvial winnowing) on the data being used to assess performance.

Cultural variation

The identification of cultural variation is even more problematic, not least because it is unclear what the null hypothesis should be. Given the current archaeological record, it is quite easy to fail to falsify the assumption of either similarity or difference, and neither should be taken as a particularly strong test of the alternative hypothesis. A more balanced approach would place equal focus on corroborative evidence, considering positive indications of similarity or difference as a complement to the strict standard of falsification invoked by Isaac's (1984) method of residuals.

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Similar problems have confronted researchers studying animal cultures, who have often adopted a "process of elimination" approach analogous to the method of residuals. As Byrne (2007) explains, however, the actual elimination of all possible non-cultural explanations is pragmatically impossible, even in living populations. Furthermore, this approach will fail to recognize behaviors as cultural if they are also constrained by environmental variation. These problems only become worse with archaeological data sets and when dealing with stone tools that clearly had an ecological function.

As an alternative, Byrne proposes the combination of *intricate complexity* with *near ubiquity* as a hallmark of cultural transmission. He argues that intricately complex behavior patterns are highly unlikely to be invented multiple times. If these behaviors are nevertheless ubiquitous in a population, it may be concluded that they have been culturally transmitted. These criteria seem suitable for application to archaeological data and are adopted here. Nevertheless, important issues remain. The most important of these are how to quantify "complexity" and establish a threshold level for the recognition of cultural transmission.

Some possibilities for quantifying lithic technological complexity include measuring the length, hierarchical depth (Stout et al., 2008), and/or number of procedures (Gowlett, 1984) involved in tool making action sequences. Ultimately, it is to be hoped that a principled means of comparing such measures can be developed, perhaps by borrowing from information theory (e.g., Suzuki et al., 2006). Establishing a particular threshold at which to infer cultural transmission will similarly require extensive research into the mechanisms involved in the social reproduction of lithic technologies (e.g., Stout, 2005; Mesoudi and O'Brien, 2008). For the time being, degrees of intricate complexity will still have to be argued on a case-by-case basis using relatively informal criteria.

The appropriate threshold for confirming cultural transmission between sites should also vary in relation to spatiotemporal patterning. Increasing spatiotemporal scale increases the number of individuals involved, thus increasing the probability of independent invention and making it more difficult to rule out multiple origins (Whiten et al., 2001). If complexity is accompanied by near ubiquity within spatiotemporally contiguous occurrences, then the case for a shared cultural tradition is somewhat strengthened. Conversely, if examples of the putative tradition are widely separated in space and/or time and interspersed with different behavioral variants, then the required complexity threshold to infer connection must become even higher. Such arguments have been controversial even in technologies much more complex than the Oldowan (e.g., Bradley and Stanford, 2006).

It is thus helpful to complement this confirmatory approach to cultural continuity by using the method of residuals to assess evidence of discontinuity. Clearly, the presence or absence of particular technological variants might result from economic and ecological rather than cultural factors. The presence of multiple "activity facies" within a single techno-cultural tradition is a prime example. Before such variation is interpreted as evidence of cultural difference it is necessary to show a stable pattern of shared differences between sites that is demonstrably independent of confounding factors. This conservative approach will likely miss some actual cultural distinctions, but is necessary if it is considered important to avoid false positives. By combining this with appropriate confirmatory tests for the presence of cultural continuity, it should also be possible to avoid false negatives. The result is likely to be a great deal of uncertainty regarding the presence and nature of Oldowan cultural variation, but uncertainty seems appropriate given the currently available evidence.

Interpreting variation at Gona: methods

To implement these theoretical perspectives, it is necessary to identify reliable archaeological indicators of hominid technological performance. Details of the methods of lithic analysis employed in this study are presented in the Supplementary Online Materials. Here we discuss the relevance and interpretation of the particular indicators used. This is necessary due to the multiplicity of influences and interactions potentially contributing to technological variation. For heuristic purposes, aspects of variation may be divided into four levels: 1) 'ultimate' ecological, biological, and cultural explanations, 2) 'proximate' technological variables, 3) concrete behavioral manifestations of these variables, and 4) archaeologically visible indicators of these behaviors.

Unfortunately, there are no privileged archaeological indicators of culture and cognition that are not also impacted by ecological and economic factors, and vice versa. Particularly notable are the complex, two-way relationships between technological variables and hominid behaviors. For example, core scar patterns are a fairly direct indicator of reduction strategies; however, reduction strategies may reflect cognitive performance as well as cultural tradition. Cognitive performance in turn is conditioned by the effectiveness of knapping techniques, which are an expression of sensorimotor performance under the influence of raw material selection, and so on. Furthermore, possible taphonomic influences on artifact representation (e.g., winnowing and fragmentation) must also be considered. Nevertheless, some relationships are likely to be more robust than others, such as the causal paths leading from: 1) ecological context to raw material frequencies, 2) species-typical sensorimotor capacities to artifact size and shape, 3) species-typical cognitive capacities to core scar patterns and technological flake category, and 4) from cultural transmission to core scar patterns and technological flake category. Paths 2, 3, and 4 are central to the arguments being presented here. Relevant indicators are discussed below.

Raw material frequencies

Raw material observations were recorded using methods established by Stout et al. (2005), and include data on groundmass texture and the average size and percentage of phenocrysts as well as raw material type. These variables are designed to capture technologically-relevant aspects of variation and will reflect a combination of intentional selection and hominid transport patterns as conditioned by availability, cognitive appreciation of desirable characteristics, and, perhaps, culturally transmitted preferences.

Artifact type frequencies

Artifact types include various core forms (after Toth, 1982), four debitage types (whole flakes, split flakes, proximal snap flakes, and angular fragments), and pounded pieces. Some types, such as the distinctive cores, flakes, and pitted anvils produced by bipolar flaking (Barham, 1987; Jones, 1994), are directly indicative of particular knapping techniques and thus provide evidence of sensorimotor performance. Debitage types can also provide evidence of sensorimotor performance, insofar as unskilled knappers are expected to produce higher proportions of angular fragments (Stout and Chaminade, 2007 and unpublished data), and the frequency of split flakes appears to be related to the percussive force employed (Toth et al., 2006). However, it is important to recognize that debitage type frequencies are also potentially influenced by raw material fracture properties, hominid transport (Toth et al., 2006), *in situ* fragmentation (Hovers, 2003), and fluvial winnowing (Schick, 1986).

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Artifact size and shape

The size, mass, and morphology of artifacts can act as important indicators for everything from taphonomic disturbance to tool function and hominid knapping skill. For example, artifact size distributions are a key indicator of fluvial transport (Schick, 1986). Of particular interest in the current study are relationships between flake morphology, skilled knapping technique, and hominid sensorimotor capacities.

In stone knapping, sensorimotor performance is evident in the effective control of elementary percussive gestures (Bril et al., 2000, 2005). For Mode I technologies, this includes the ability to identify and utilize advantageous platform angles and to deliver sufficient force with accuracy to detach large, invasive flakes (Toth et al., 2006; Stout and Chaminade, 2007; Stout et al., 2008). Such flakes are typically distinguished by external platform angles (EPAs) in the range of 70–80° (Pelegrin, 2005), large size relative to cores, and length greater than or equal to breadth (i.e., breadth/length $\leq$1.0). The removal of such large, invasive flakes permits the efficient and complete reduction of cores without the premature exhaustion of core angles (Stout et al., 2008).

Mode I flake size and shape (particularly the ratio of cutting edge to mass) has also been considered relevant to understanding economic function (Braun and Harris, 2003). In general, excessive flake thickness is considered 'wasteful,' as it depletes core volume while producing relatively little cutting edge. There is no standard value for optimum flake thickness, but breadth/thickness ratios provide a point of comparison between assemblages.

Core scar counts and percent cortex

Core scar counts and percent cortex are presented as two proxy measures for reduction intensity. Variation in reduction intensity is most commonly attributed to underlying economic and raw material variables and is believed to have important effects on artifact frequencies, size, and morphology (e.g., Rolland and Dibble, 1990). Reduction intensity can also be seen as an indicator of knapping skill, insofar as unskilled knappers may not be capable of efficiently and completely reducing Mode I cores (Stout and Semaw, 2006; Toth et al., 2006; Stout and Chaminade, 2007). The latter interpretation is the most salient for the current investigation.

In general, scar counts should increase and percent cortex cover decrease as cores are more intensely reduced. These relationships are complicated by scaling effects on surface to volume ratios and the erasure of previous flake scars by subsequent removals (Braun et al., 2005). These effects may be controlled to some extent by correcting for core size (Braun et al., 2005), thus providing a rough estimate of reduction intensity. The imprecision of such estimates can be problematic in addressing ecological questions about raw material economy but is less troublesome for arguments about knapping skill, which (for the time being) refer only to relatively broad categories of 'efficiently reduced' vs. 'prematurely exhausted' cores. In the current study, size-corrected scar counts and percent cortex were used to provide a quantitative standard of comparison for reduction intensity across sites. This was complemented by the analysis of technological flake types, Minimum Analytical Nodule Analysis (MANA) of flakes and associated cores (see below), and qualitative evaluation of individual cores.

Technological Flake Categories

A widely used system of Technological Flake Categories was developed by Toth (1982). Six types are defined on the basis of the occurrence of cortex on the platforms and dorsal surfaces of whole flakes: type 1 flakes have cortical platforms and dorsal surfaces, type 2 flakes have cortical platforms and partially cortical dorsal surfaces, type 3 flakes have cortical platforms and non-cortical dorsal surfaces, type 4 flakes have non-cortical platforms and cortical dorsal surfaces, type 5 flakes have non-cortical platforms and partially cortical dorsal surfaces, and type 6 flakes have non-cortical platforms and non-cortical dorsal surfaces. Experimental studies have shown that the proportional representation of Technological Flake Categories provides information about reduction strategies and stages (Toth, 1982, 1987). In particular, cortical platform flakes (types 1–3) are associated with unifacial flaking, and flakes with little or no cortex (types 3, 5, and 6) are associated with later stage flaking. The representation of Categories may also be influenced by core size (Toth, 1997; Braun et al., 2008b), with larger cores producing relatively fewer types 1–3. In this study, Technological Flake Categories were used primarily as evidence of reduction strategies, and secondarily to complement core scar counts and minimum nodule analyses in inferring reduction stages.

Minimum analytical nodule analysis (MANA)

Refitting is a highly effective technique for reconstructing reduction strategies (Delagnes and Roche, 2005) and inferring transport patterns from missing pieces (Kroll, 1997). However, many assemblages do not contain a large number of refitting pieces, particularly if transport has been extensive. In such cases, MANA can be a useful technique (Larson and Kornfeld, 1997). MANA groups pieces according to the distinctive raw material characteristics of individual nodules and thus provides evidence of the number of different nodules reduced at a site as well as the number, size, and type of pieces present from each nodule. This evidence is useful for inferring raw material selection and artifact transport patterns, as well as reduction intensity. MANA results are not as definitive as refitting but do provide useful information that would otherwise be unavailable (Larson and Kornfeld, 1997). MANA results are most robust in assemblages, like OGS-7, that contain highly variable and distinctive raw materials. For this reason MANA was conducted with the OGS-7 assemblage but has not been attempted with the somewhat less differentiated assemblages from EG-10 and EG-12, which are predominantly made from trachyte and rhyolite.

Core scar patterns

Patterns of flake scars left on cores provide a relatively direct indicator of reduction strategies. Nevertheless, these patterns only record the final removals from a core, and it is possible that earlier removals may have followed a different pattern or patterns. For this reason it is important to consider other lines of evidence, such as Technological Flake Categories, which can provide independent evidence of reduction strategies.

In the current study, scar patterns were systematically recorded using the typology presented by de la Torre et al. (2003). This system is based on the location (unifacial, bifacial, multifacial), direction (unidirectional, bidirectional, centripetal), and angle (simple, abrupt) of flake removals and includes eight distinct reduction strategies (Fig. 2). Insofar as they vary in complexity, the occurrence and distribution of these reduction strategies is relevant to inferring hominid cognitive performance and cultural traditions. The former is indicated by the occurrence of cognitively complex behavior in an assemblage and the latter by the near ubiquity of intricately complex variants within and between sites.

Our ability to compare the complexity and cognitive demands of different reduction strategies remains in its infancy. Available evidence suggests that hierarchical organization, and particularly the nesting of subroutines within ongoing goal-directed sequences

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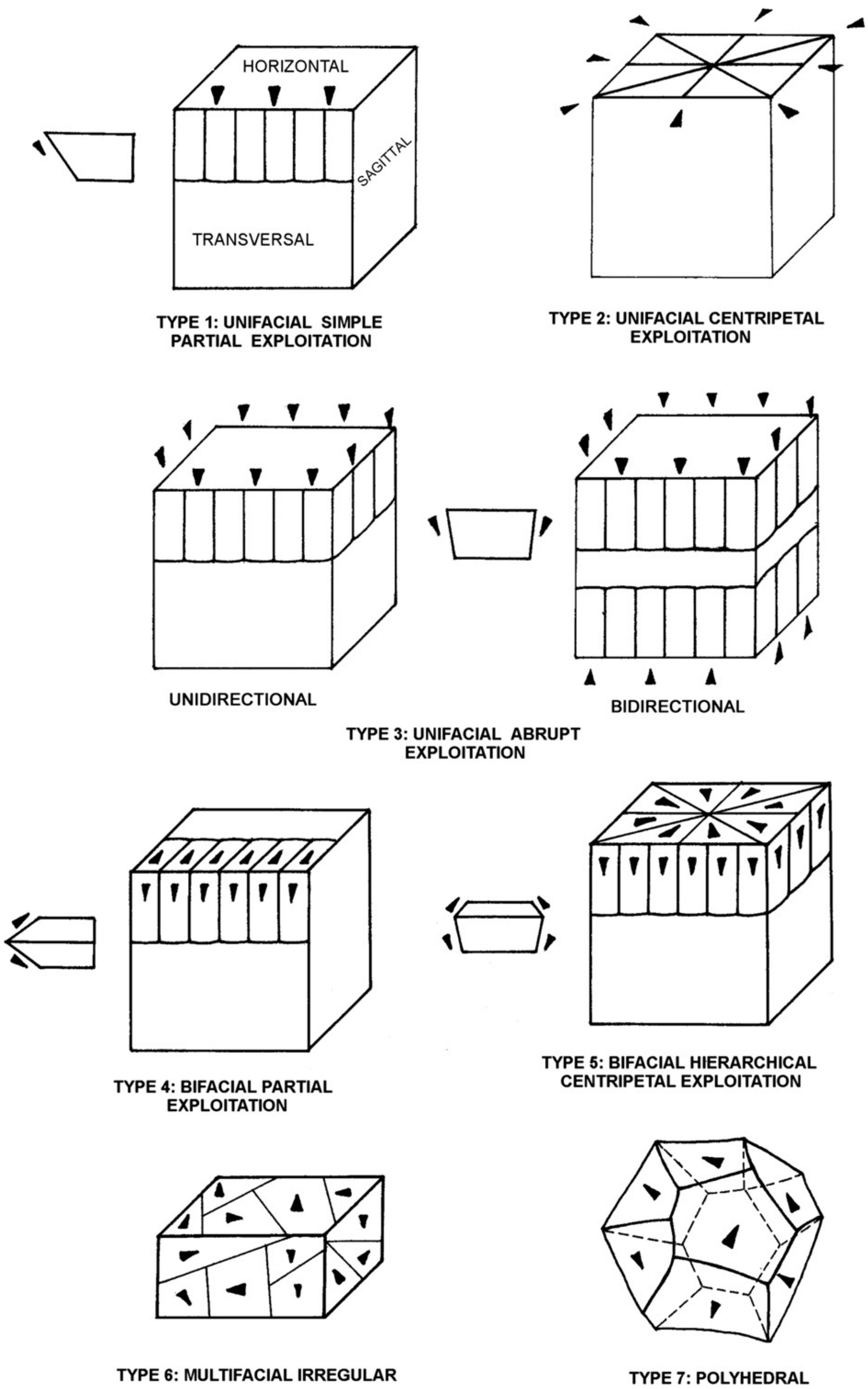

Fig. 2. Idealized knapping methods of de la Torre et al. (2003). Figure courtesy of Ignacio de la Torre.

(Byrne, 2004), is one of the more important indicators of cognitive complexity (Stout et al., 2008). According to this criterion, reduction strategy 6 (irregular multifacial) would be the simplest since the location of each flake removal need only be determined based on the current state of the core (i.e., location of viable angles and surfaces). Strategies 1–4 (i.e., simple unifacial and bifacial strategies) would all be of intermediate cognitive complexity as they involve not only responsiveness to current core configurations but also a simple (i.e., Markovian) chaining together of flake removals in which the location of the next removal is determined from the previous one according to a simple rule (e.g., vertically adjacent, horizontally adjacent, alternate face). It is not possible to explain the consistent appearance of these knapping patterns without recourse to some such behavioral rule because the patterns are underspecified by the natural variability and multiple action possibilities typically afforded by cores (e.g., unexploited possibilities for bifacial/multifacial removals seen in Figs. 7 and 9 e and f). Strategies 5 (bifacial hierarchical centripetal) and 7 (polyhedral) would be the most complex because both are argued (de la Torre et al., 2003; Roche, 2005) to require an additional level of

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subordinate flake removals specifically intended to maintain or manipulate flaking angles and surfaces. In general, the simple presence of particular strategies in an assemblage should be sufficient to infer the requisite cognitive capacities. Arguments about cultural transmission are somewhat more demanding.

According to the above complexity estimates, near ubiquity of strategy 6 would provide only relatively weak evidence of cultural transmission. Although no objective standard exits, strategies 1–4 provide stronger cases for cultural transmission. It remains an open question whether they are sufficiently complex to imply cultural connections between widely and/or discontinuously dispersed sites. Ubiquity of strategies 5 or 7 would provide the strongest evidence of cultural transmission and of connections between dispersed sites.

Results and discussion

Detailed results of all analyses are presented in the Supplementary Online Materials (SOM). Here we limit discussion to the major findings regarding site formation processes and hominid behaviors. Table 1 summarizes the artifact samples (all pieces >25 mm) from the three sites.

Assemblage integrity

Current analyses of EG-10 and EG-12 corroborate Semaw's (1997, 2000, 2006) conclusion that the assemblages are minimally disturbed. This is supported by artifact size distributions that approximate experimental predictions (Schick, 1986) for undisturbed assemblages (Fig. 3), by artifact freshness, by a lack of preferential artifact orientation or vertical dispersion, and by the fine-grained sedimentary contexts of the sites. EG-10 displays a relatively high proportion of angular fragments (SOM Table 2) which may reflect local site formation processes (Semaw, 1997: 107), perhaps including pedogenesis, sediment compaction, and/or trampling (Hovers, 2003), leading to *in situ* fragmentation. Both EG-10 and EG-12 are located in vertisolic sediments, and fragmentation through argilliturbation (Duffield, 1970) is a possibility, although there is little evidence of the surface modification, edge damage, and vertical dispersion of artifacts that would normally be associated with this process. It is also possible that the preservation and recovery of a larger sample from EG-10, in excavations that included two distinct artifact horizons as well as intervening sediments, may have provided a more representative sample of angular fragments from this site. The high proportion of angular fragments at EG-10 is unlikely to indicate differences in raw material properties or knapping skills as all other relevant indicators (e.g., raw material frequencies by artifact type, artifact size and shape) show a very close affinity with EG-12.

Assemblage integrity at OGS-7 is remarkable. As previously reported (Semaw et al., 2003), artifacts were recovered from a tightly restricted (<10 cm thick) layer located at a local contact between coarse sand and bedded floodplain silts within a classic fining-upward sequence. This stratigraphic position indicates a channel bank or margin setting, and the sediments appear undisturbed by either bioturbation or argilliturbation. More than 75% of the excavated assemblage comprises pieces <20 mm in

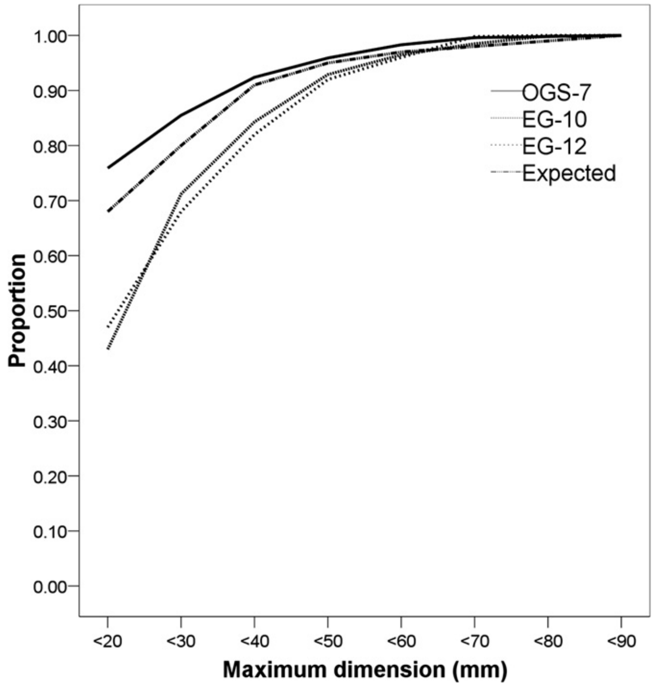

Fig. 3. Artifact size distributions compared to experimentally derived expectations (data from Schick [1986]) for a complete assemblage.

maximum dimension, and pieces display a clear horizontal clustering without preferential orientation. All of these observations are consistent with on-site flaking and minimal disturbance of the assemblage. None of the sites under consideration show evidence of major taphonomic influences that might noticeably affect archaeological indicators of hominid behavior.

Transport patterns

As with assemblage integrity, the primary purpose of investigating artifact transport patterns in the current study was to assess possible confounding influences on indicators being used to infer other aspects of behavior and cognition. More specific details are presented in the SOM.

Experimental replication of EG-10 and EG-12 by Toth et al. (2006) suggested a pattern of hominid artifact transport involving: 1) the introduction of partially flaked cores, 2) late stage, high intensity flaking on site, and 3) subsequent removal of large, sharp flakes for use elsewhere on the landscape. Their results and interpretation are consistent with the results of our own Technological Flake Category, core flake scar, and core percent cortex analyses. This evidence of transport raises the possibility that artifact type frequencies and metrics will underestimate hominid sensorimotor performance in

Table 1
All Pieces >25 mm

Site	Cores	Whole flakes	Split flakes	Angular fragments	Total
EG10	16	72	43	154	285
EG12	9	61	37	69	176
OGS7	7	76	22	80	185

Table 2
OGS-7 Minimum Analytical Nodules (excavated pieces >25 mm)

Material	Cores	Analytical nodules	Total pieces	Pieces/Nodule	Range
Quartz Latite	0	2	17	8.5	1–16
Rhyolite	2	4	30	7.5	3–12
Latite	1	4	25	6.3	4–10
Other (volcanic breccia)	1	1	6	6.0	6
Trachyte	1	3	12	4.0	2–7
Vitreous volcanic	0	4	10	2.5	1–4
Aphanitic	2	6	14	2.3	1–5
Basalt	0	1	1	1	1

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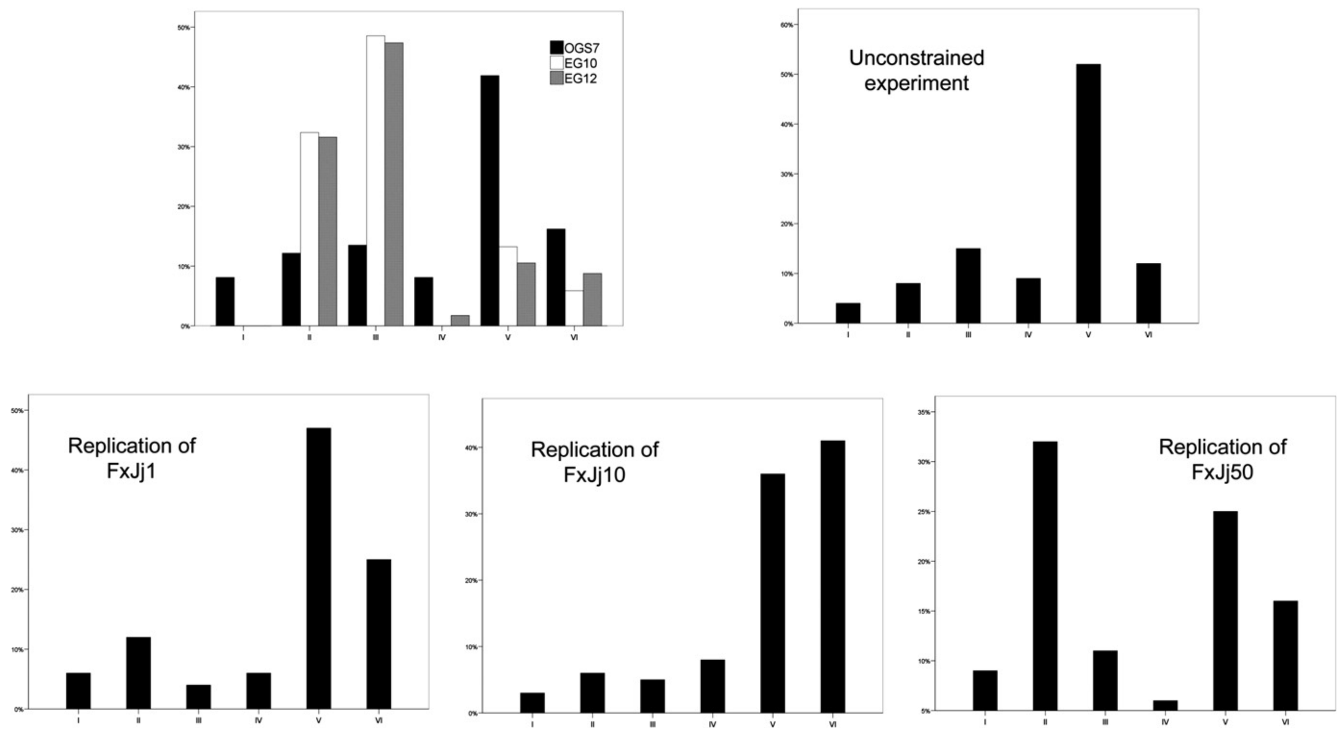

Fig. 4. Technological Flake Category distributions from Gona in comparison to systematic replication experiments reported by Toth (1987).

producing large, invasive flakes at these sites. It is less likely that hominid capacities for intensive core reduction will be underestimated.

In contrast to the EG sites, there is substantial evidence to suggest an equal representation of earlier and later reduction stages at OGS-7. Out of the seven cores recovered from the excavation, MANA found three to be associated with early stage flakes equal to or larger in maximum dimension than the remaining core. Refits in the assemblage similarly include small, final stage fits to cores as well as front-to-back fits of larger, early-stage pieces. The presence of early stage reduction at OGS-7 is further attested by a relatively high percentage of type 1 flakes (8%) and the occurrence of flakes with a greater maximum dimension than the largest core (5%). By comparison, type 1 flakes are almost completely absent from EG-10 and EG-12 (<1%), and no flakes are larger than the largest core. Finally, the overall distribution of Technological Flake Categories at OGS-7 closely approximates that seen in complete experimental flake populations (Fig. 4) from both unconstrained experiments

Table 3
Whole Flakes >25 mm

		Mass (g)	Maximum dimension (mm)	Length (mm)	Breadth (mm)	Thickness (mm)
EG-10 ($n = 72$)	Mean	24.9	45.7	36.1	34.5	13.6
	Median	13.5	42.0	33.0	32.0	12.0
	Range	2–160	25–85	13–72	16–73	2–32
EG-12 ($n = 61$)	Mean	21.5	44.5	34.6	35.3	12.8
	Median	15.0	43.0	31.0	32.0	11.0
	Range	1–108	25–72	15–70	14–61	3–32
OGS-7 ($n = 76$)	Mean	18.9	47.0	35.4	35.4	11.8
	Median	12.5	44.0	33.0	33.5	11.0
	Range	1–83	26–85	21–75	12–85	3–25

		Breadth/Length	Breadth/Thickness	EPA (°)	P. Br. (mm)	P. Th. (mm)
EG-10 ($n = 72$)	Mean	0.99	2.88	74	22.5	9.7
	Median	0.94	2.66	76	20	8.0
	Range	0.52–1.85	1.30–13.5	47–94	4–69	1–32
EG-12 ($n = 61$)	Mean	1.09	3.11	71	24.7	9.9
	Median	1.00	3.00	74	21.5	8.0
	Range	0.41–2.24	1.41–8.33	40–90	6–53	1–28
OGS-7 ($n = 76$)	Mean	1.00	3.26[a]	73	19.8	7.1[b]
	Median	1.02	2.96[a]	75	19.0	7.0[b]
	Range	0.36–1.68	1.19–10.0[a]	40–93	3–44	1–17[b]

[a] variable significantly different from EG-10 by t'-test on ranked data.
[b] variable significantly different from EG-10 and EG-12 by t'-test on ranked data.

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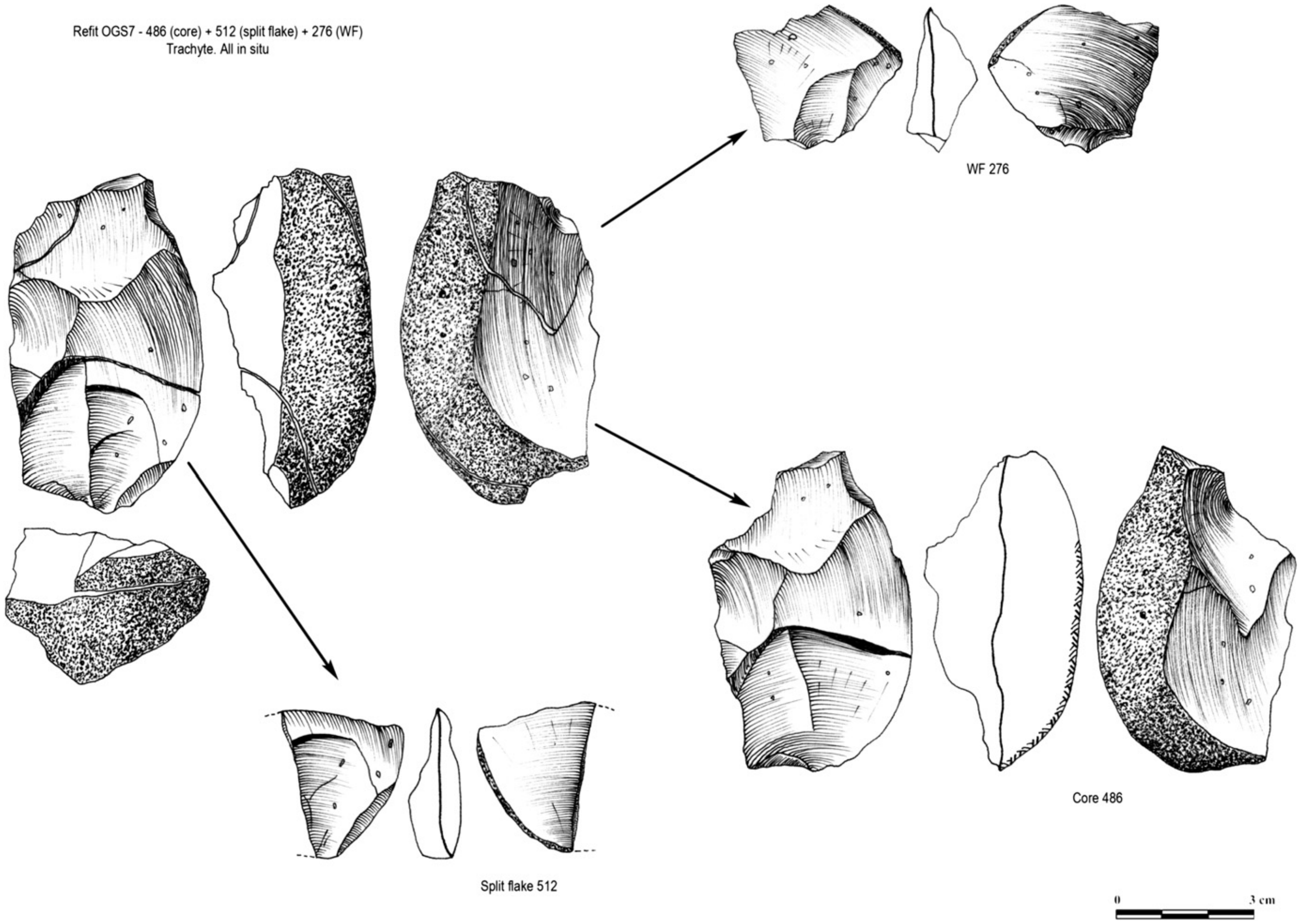

Fig. 5. An exhaustively reduced bifacial core from OGS7, showing two final stage refits.

and the core-by-core replication of Oldowan assemblages (FxJj1, FxJj10) with a strong bifacial component (Toth, 1987). This suggests that artifact frequencies and metrics at OGS-7 should provide relatively unbiased indicators of hominid performance. As might be expected, the distribution produced by the replication of FxJj50, a site with an emphasis on unifacial flaking reminiscent of EG-10 and EG-12 (Schick and Toth, 2006), more closely approximates the distributions from these sites.

It is notable that the number of pieces per analytical nodule (Table 2) at OGS-7 is generally quite low. This would usually suggest substantial transport of pieces into and/or out of the site (Larson and Kornfeld, 1997), although the small size of the excavation at OGS-7 (2.6 m^2) raises the possibility that nodules are incomplete primarily due to spatial dispersion and a small sample size. On the other hand, the number of nodules and pieces per nodule varies with raw material, with fine-grained aphanitic and vitreous volcanics being represented by the most nodules and the fewest pieces per nodule. This differential treatment is most consistent with transport and curation of these high-quality, locally scarce (Stout et al., 2005) materials. However, results and comparisons presented above provide no evidence that such transport, if it in fact occurred, systematically biased artifact frequencies, core attributes, or flake metrics at the assemblage level.

Raw material selection

Excluding indeterminate pieces, there is a highly significant difference in raw material frequencies between East Gona and OGS-7 (Pearson's Chi Square: $\chi^2 = 160.8$, df = 7, $n = 541$, $p < 0.001$). Compared with East Gona, the OGS-7 assemblage is distinguished by a greater representation (see SOM Results) of high-quality aphanitic and vitreous volcanic materials, and by a finer mean groundmass ($t' = 4.90$, df = 104.4, $p < 0.001$) for the whole assemblage. As fine-grained materials are quite scarce in local conglomerates (e.g., vitreous volcanics <1%), this clearly reflects an intentional investment in finding and selectively transporting these materials to the site.

Table 4
Variation in Oldowan knapping methods

Site[a]	Age (Ma)	Number of cores	Unifacial %	Bifacial %	Multifacial %
OGS-7	2.5–2.6	7	14	57	29
EG-10	2.5–2.6	16	75	12.5	12.5
EG-12	2.5–2.6	9	78	11	11
Lokalalei 2C	2.3	70[b]	67–97[c]	1–10[c]	1–20[c]
Fejej FJ-1	1.96	92	60	11	29
DK	1.84	69	37.5	53.4	10.1
FLK Zinj	1.76	49	50.9	49.1	0.0
FLK North 1–2	1.75	85	22.2	69.5	8.3
FxJj 1	1.88	5	20	60	20
FxJj 10	1.88	13	38	54	8
FxJj 50	1.50–1.55	63	59	37	4

[a] data from: Lokalalei (Delagnes and Roche, 2005), Fejej (de Lumley et al., 2004), DK and FLK (de la Torre and Mora, 2005), FxJj (Toth, 1997).
[b] includes 18 surface pieces.
[c] estimates only, counts not provided.

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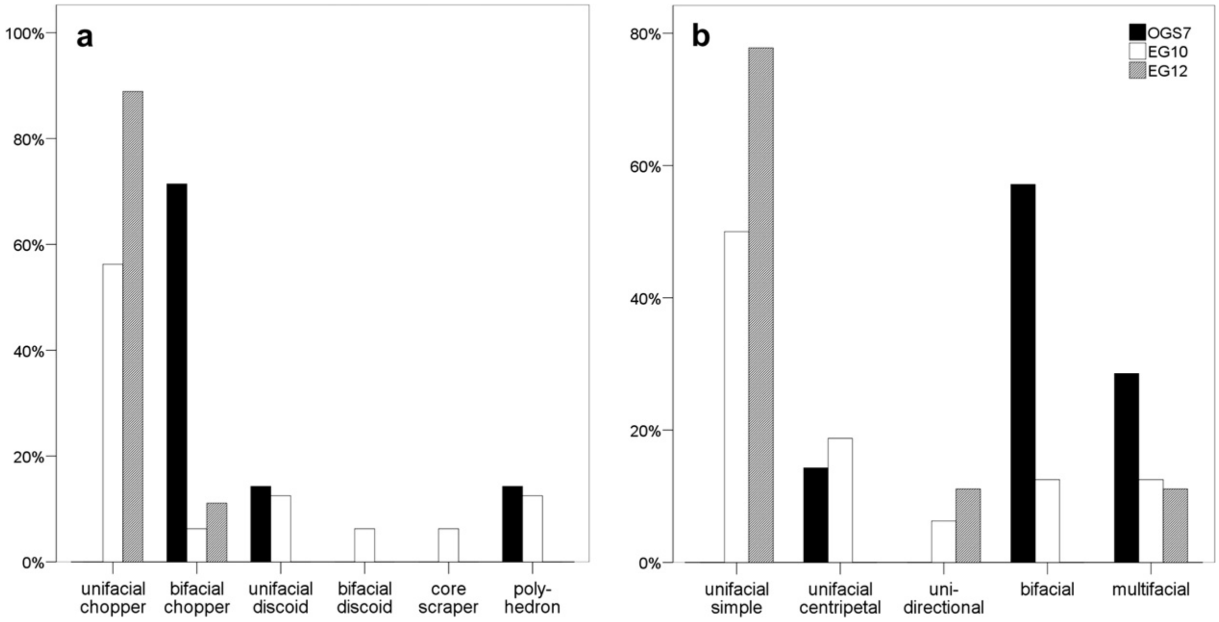

Fig. 6. Distribution of core types (a) and knapping methods (b) at EG-10, EG-12, and OGS-7.

The EG-10 and EG-12 assemblages are dominated by trachyte and, to a lesser extent, rhyolite. Trachyte is one of the higher-quality materials in the conglomerates (Stout et al., 2005) and is often available in larger nodules than the rare aphanitic and vitreous volcanics. Despite substantial reduction, cores from East Gona remain relatively large (58–105 mm), suggesting initial dimensions frequently >100 mm. This is also consistent with the >100 mm diameter refit group from EG-10 (see SOM Results). Nodule size may have been an important selection criterion at East Gona and could have contributed to the observed preference for trachyte. Some nodules may also have been selected for shape, and the simple unifacial cores ($n = 15$) in particular are relatively flat compared to the more spherical nodules typical (Stout and Semaw, 2006) of the conglomerates.

Evidence of selectivity for particular raw material types at particular sites necessarily implies sensory and cognitive capacities for the discrimination and selection of preferred materials. This is true of all three sites discussed and provides no suggestions of underlying biological differences between the toolmakers. The specific patterns of selectivity seen at OGS-7 and the East Gona sites contribute to the intricate complexity of the technological behavior in question and, in combination with the near ubiquity of particular reduction strategies (see below), help to indicate the presence of cultural transmission.

Knapping skill and techniques

Knapping technique is also uniform across the three sites and appears to be limited to the free-hand, hard-hammer, direct percussion typical of Oldowan sites. There is no evidence to suggest the presence of bipolar, anvil, or throwing techniques. As highlighted by previous descriptions (Semaw et al., 1997, 2003), all three

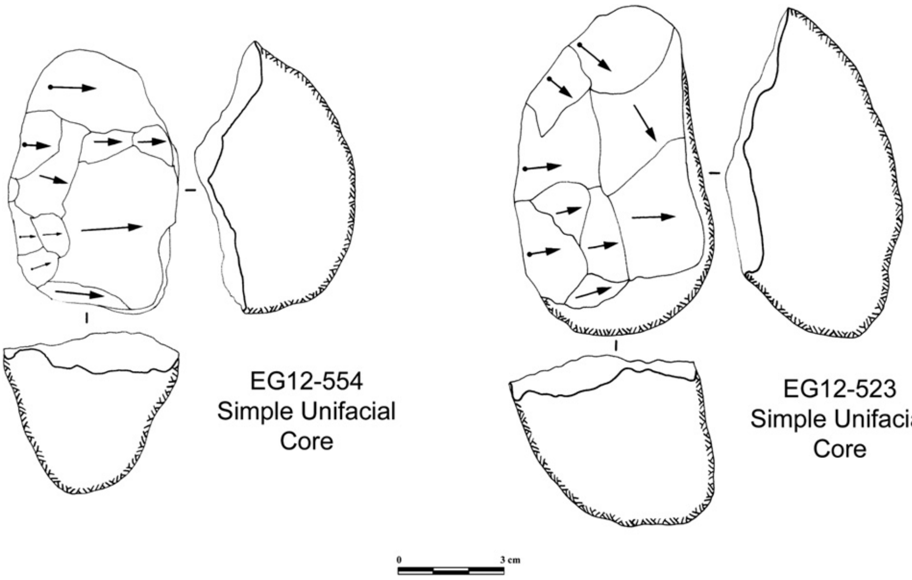

Fig. 7. Illustrations of simple unifacial cores from East Gona.

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sites considered here provide evidence of skilled flaking. Cores are heavily and systematically reduced and there are numerous large, well-formed flakes with good cutting edges, despite the likelihood that many such pieces from EG-10 and EG-12 may have been removed for use elsewhere (Toth et al., 2006).

Cores from OGS-7 are small but preserve a relatively high number of flake scars (Table 3), with a mean 0.08 scars per gram. Similar scar-to-mass ratios have been interpreted elsewhere as indicating "extensive" and "near exhaustive" (Braun et al., 2009: 103–104) reduction of cores. The OGS-7 cores also display a relatively small percentage of remnant cortex, which is again consistent with exhaustive reduction. Most importantly, exhaustive reduction is indicated by direct technological assessment of the cores (Figs. 5, 8, 10), which are quite heavily worked and present little opportunity for further reduction.

Cores from EG-10 and EG-12 are larger (Table 3), preserve fewer scars per gram (mean 0.04 and 0.03, respectively), and have a greater percentage of remnant cortex. This might suggest less reduction, but direct comparisons are complicated by the greater prevalence of unifacial flaking at East Gona (see below). Logically, flaking limited to a single surface would be expected to erase previous flake scars at a greater rate and to preserve a higher percentage of cortex. In technological terms, unifacial cores from East Gona do appear extensively or even exhaustively reduced on their flaked surfaces, even though they may still offer viable opportunities for bifacal or multifacial removals elsewhere (e.g., Figs. 7 and 9e and f). Potential explanations for this emphasis on unifacial reduction are considered below but cannot include deficits in sensorimotor skill given the effective maintenance and reduction of single surfaces that is evident. In fact, Toth et al. (2006) estimate that an average of 63% of initial mass has been removed from cores at EG-10 and EG-12 despite the emphasis on unifacial flaking.

It is clear that knappers at all three sites were sufficiently skilled to reduce cores efficiently within a given reduction strategy. This implies consistently high levels of sensorimotor performance across sites, although differences in raw material selection and knapping strategies do place some limits on the comparison. Nevertheless, the available evidence is inconsistent with the existence of pronounced differences in sensorimotor performance that might be indicative of species-level differences in the toolmakers.

Metric analyses of whole flakes support the same interpretation. There are no significant differences in the size of whole flakes across the three sites, and all display EPAs centered in the optimal 70°–80° range, with mean breadth/length ratios approximating 1.00 (Table 4). It is true that flakes at OGS-7 are relatively larger compared to the diminutive cores from the site; however, it has already been noted that hominid transport patterns may have deleted some larger flakes from the East Gona assemblages. Whole flakes from OGS-7 are also relatively thinner than those from EG-10 and have thinner platforms than both East Gona sites, which might reflect greater percussive precision (Stout, 2002; Stout and Semaw, 2006). However, the greater prevalence of bifacial flaking and non-cortical platform flakes at OGS-7 makes such direct comparison problematic. In sum, there are patterns in the core and flake data to suggest that the sensorimotor performance of toolmakers at OGS-7 may have been slightly more refined, but these small differences might easily be attributed to confounding factors and do not support the presence of multiple toolmaking species.

Reduction strategies

The most striking and important finding of the current investigation is that, while OGS-7 and the East Gona sites are quite similar in terms of knapping techniques and skills, they differ dramatically in knapping strategies. As previously reported (Semaw, 2000, 2006; Toth et al., 2006), the EG-10 and 12 assemblages are dominated by unifacial cores (59%; Fig. 6a) and the cortical platform flakes (80%; Fig. 4) typically produced by unifacial flaking. In contrast, 86% of the cores from OGS-7 are bifacial or multifacial and non-cortical platform flakes predominate (66%). The representation of different flaking methods at OGS-7 is comparable to many later Oldowan sites at Olduvai and Koobi Fora (Table 4), and directly contradicts the idea that Pliocene hominids were restricted to predominantly unifacial flaking.

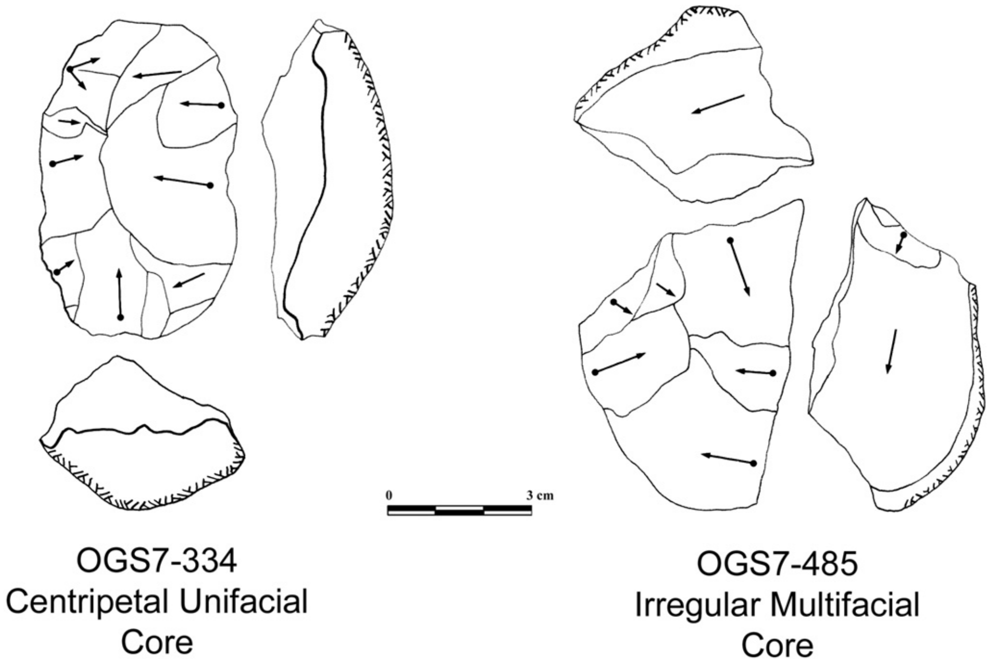

Fig. 8. Illustrations of exhaustively reduced centripetal unifacial and irregular multifacial cores from OGS-7.

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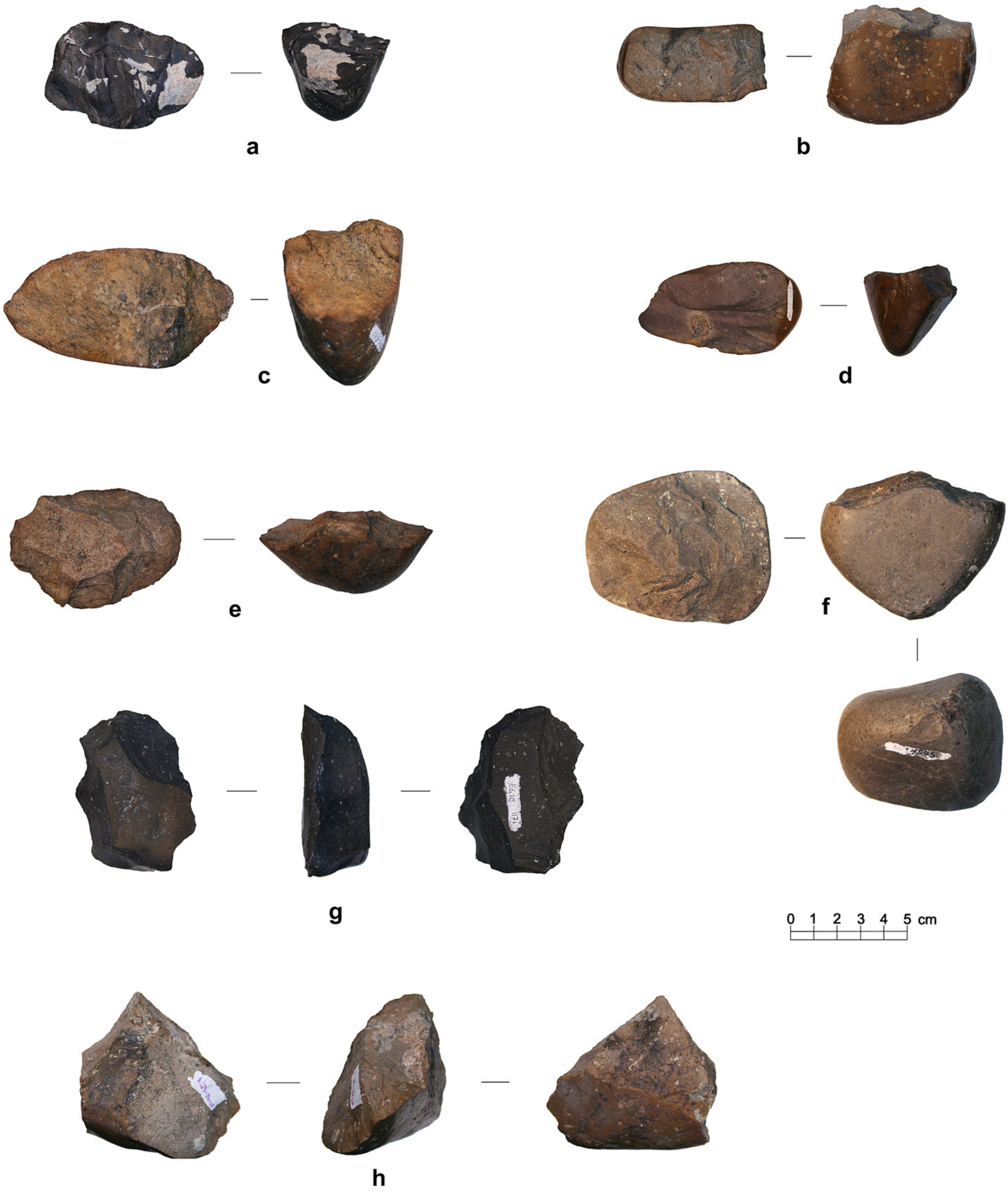

Fig. 9. Photographs of EG10 and EG12 flaked pieces: Simple unifacial (a, b, c, d), unifacial centripetal (e, f), bifacial (g), and multifacial (h) cores. Note battering on the cortical surface of (f) indicating use as a hammerstone.

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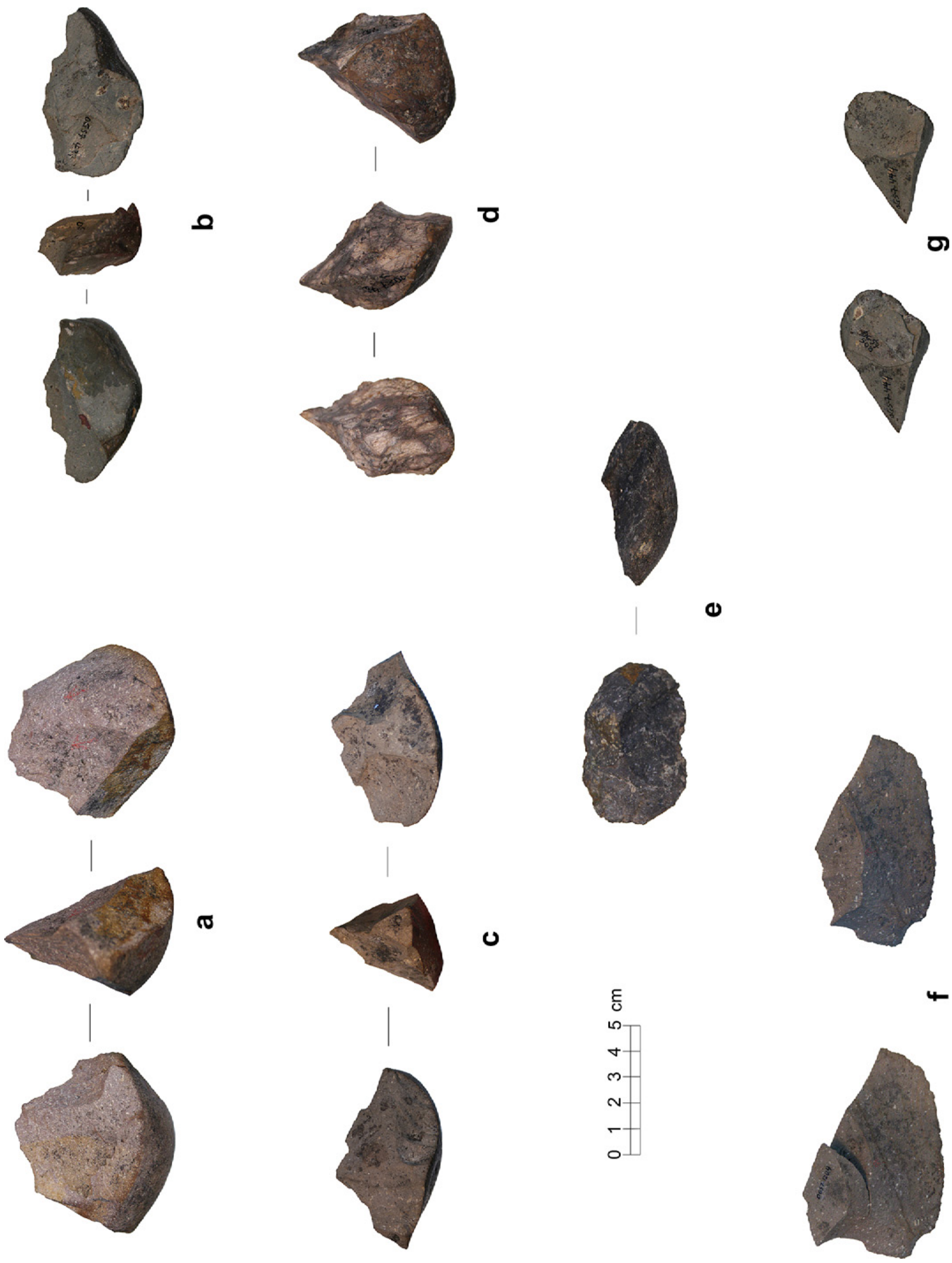

Fig. 10. Photographs of OGS-7 flaked pieces: Bifacial (a, b, c), multifacial (d), and unifacial centripetal (e) cores, and refitting removals (f, g) from Detached Pieces.

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Five of the eight Mode I reduction methods described by de la Torre et al. (2003) were observed: 1) simple unifacial, 2) centripetal unifacial, 3) unidirectional, 4) partial bifacial, and 5) irregular multifacial. The distribution of these methods is presented in Fig. 6b, with specific examples shown in Figs. 5 and 7–10. It is notable that hierarchical bifacial centripetal and polyhedral methods are absent from all three sites. Two cores do display a combination of unifacial and unidirectional removals; however, in each case the unidirectional removals are relatively few in number and the cores were classified according to the dominant, unifacial, mode. The knapping surfaces on these cores are clearly not related to each other in the systematic way characteristic of bifacial hierarchical centripetal reduction as described by de la Torre et al. (2003) in later (1.6–1.4 Ma) Mode I assemblages from Peninj.

Five cores (2 from EG-10, 1 from EG-12, and 2 from OGS-7) were classified as irregular multifacial. Two of these (from EG-10 and OGS-7, Figs. 9h and 10d) could be considered polyhedral in the sense that they show a clear intersection of three worked edges (Leakey, 1971; Isaac et al., 1997). However, they do not display the organized knapping and intentional shaping said to distinguish the polyhedral method (Texier and Roche, 1995), and they lack the core angles of more than 90° considered by Roche (2005) to be diagnostic of intentional polyhedral shaping.

Although the differing emphasis on bifacial vs. unifacial strategies at OGS-7 vs. EG-10 and EG-12 is quite clear, it is important to note that there is substantial overlap in the presence of different strategies across the sites, including a clearly bifacial discoid from EG-10 (Fig. 9g). Furthermore, the bifacial and unifacial strategies involved can be considered of comparable complexity (see Methods). The two reduction strategies (bifacial hierarchical centripetal and polyhedral) that would imply more complex cognitive performance are absent from all three sites. The observed patterns thus fail to provide evidence of differences in underlying cognitive capacities that might imply the presence of multiple hominid species.

This leaves the question of cultural transmission. With frequencies approaching 60% or more (Fig. 6b), it seems reasonable to characterize unifacial and bifacial reduction strategies as near ubiquitous at their respective sites. Considering the level of intricate complexity involved in specifying these particular strategies (i.e., specific rules governing the placement of removals with respect to previous removals), this provides a case for some form of cultural transmission within sites. Associated patterns of idiosyncratic raw material selectivity provide evidence of additional complexity that further support this case.

The spatial and stratigraphic proximity of EG-10 and EG-12 coupled with the near ubiquity of the same complex technological behaviors at both sites provide reasonable support for a cultural connection. This is not the case with OGS-7 and the East Gona sites, which do not share the same complex and ubiquitous technological patterns. This absence of evidence for cultural continuity does not, however, constitute strong evidence of cultural difference. That would require a stable pattern of shared differences that were clearly independent of confounding ecological and economic factors. In fact, technological differences between OGS-7 and the East Gona sites are thoroughly confounded by ecological and economic differences.

As described above, OGS-7 formed in a channel bank or margin context while both EG-10 and EG-12 were located on a proximal floodplain. The East Gona sites would thus have been located somewhat further from the main channel and in a different ecological context, most likely the ecotone of edaphic grassland and gallery forest bordering the Ancestral Awash River (Quade et al., 2004). The economic impacts of these differences in ecological context might contribute to observed differences in raw material selection, artifact transport, and reduction strategies between OGS-7 and East Gona. It would thus be premature to conclude that OGS-7 and the East Gona sites represent distinct techno-cultural traditions, although this cannot currently be ruled out. Additional evidence is needed.

Such evidence can only come from further fieldwork and analysis. For example, the site of OGS-6 (Semaw et al., 2003; Dominguez-Rodrigo et al., 2005), located in close spatial and stratigraphic association with OGS-7, has yielded an excavated lithic assemblage of 12 whole flakes, 8 split flakes, and 19 angular fragments. This is obviously too small for extensive analysis but it is nevertheless interesting to note that none of the whole flakes display cortical platforms. This is suggestive of technological similarities to OGS-7, even though OGS-6 is located in a floodplain depositional environment more similar to EG-10 and EG-12. If such patterns of apparently ecologically-independent variation are confirmed through further survey and excavation at Gona, they would be consistent with the existence of discrete cultural variants (although it would still be difficult to rule out the possibility of activity variants not linked with ecological differences).

Conclusions

Evidence from the earliest known archaeological sites, EG-10, EG-12, and OGS-7, is inconsistent with the existence of a "pre-Oldowan" phenomenon involving lower skill levels and/or simpler reduction methods. Cores at all three sites were efficiently reduced through the production of large, invasive flakes, using a range of strategies comparable to that seen in later Oldowan times, including ubiquitous bifacial reduction at OGS-7. More complicated strategies for polyhedral shaping and hierarchical reduction that are absent at Gona also seem to be absent from later Oldowan sites. Most, if not all, Oldowan polyhedrons appear to be byproducts of exhaustive multidirectional flake production (Sahnouni et al., 1997) rather than intentionally shaped artifacts, and bifacial hierarchical centripetal reduction has only been identified in younger assemblages currently thought to represent Mode I facies of the early Acheulian (de la Torre, pers. comm.). Available evidence of Oldowan flaking skills and strategies from Gona and elsewhere (Toth, 1997; de la Torre, 2004; de la Torre and Mora, 2005; Delagnes and Roche, 2005; Braun et al., 2009) thus fails to reveal clear inter-assemblage variation or progressive change in sensorimotor or cognitive capacities that might indicate the presence of multiple toolmaking species. It remains possible that multiple species made Oldowan tools, but this is not evident from the archaeology.

Much the same may be said regarding the existence of multiple cultural variants within what is currently recognized as the Oldowan. Technological differences between sites that might suggest such traditions are thoroughly confounded with ecological and economic variation (cf. Braun et al., 2009), as illustrated here in the comparison of East Gona with OGS-7. However, the difficulty of demonstrating cultural differences is not itself a strong case for cultural continuity. Such a case can be made for the sites of EG-10 and EG-12, which share specific technological features and are located in close spatiotemporal proximity, but loses force over the vast, heterogeneous range of the Oldowan. As numerous researchers have argued (e.g., Isaac, 1976; Toth, 1985), the Oldowan Industrial Complex is unified by little more than the controlled use of conchoidal fracture to produce sharp edges (i.e., Mode I technology). It must be considered that this basic principle could have been discovered multiple times over such a vast range of time and space.

Following Whiten et al. (2001), three models of Oldowan origins may be considered: diffusion from a unitary origin, diffusion from multiple origins, and diffusion with differentiation. Current evidence shows an abrupt appearance at c. 2.6 Ma of fully

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competent Mode I tool making at multiple high density sites at Gona (Semaw, 2006) accompanied by cut-marked bone at OGS-6 (Semaw et al., 2003) and the nearby (c. 90 km) Middle Awash site of Bouri (de Heinzelin et al., 1999). By c. 2.4–2.3 Ma, Mode I tools appear elsewhere in the Afar (e.g., Kimbel et al., 1996) as well as further south at Omo (Howell et al., 1987; de la Torre, 2004) and the Turkana Basin (Brown and Gathogo, 2002; Delagnes and Roche, 2005). They are present throughout much of East (Leakey, 1971; Isaac and Isaac, 1997; Braun et al., 2009), North (Sahnouni, 2006), and South Africa (Kuman, 2007) by c. 2.0–1.7 Ma. This distribution is most consistent with diffusion of Mode I flaking from a single origin in the Afar Rift c. 2.6 Ma, accompanied by the adaptation of specific technological practices (e.g., raw material selection and associated reduction strategies) to local environments and possibly a limited amount of cultural drift (Boyd and Richerson, 1985).

Of course, the early record remains quite sporadic, and future discoveries may alter the apparent pattern of diffusion. It should nevertheless be stressed that years of intensive survey in older (c. 2.7–2.6) deposits at Gona immediately overlying a region-wide unconformity (Quade et al., 2004) have failed to yield evidence of flaked stone or modified bone prior to the sudden appearance of high density sites at EG-10, EG-12, and OGS-7. Whether it had multiple origins or just one, it seems clear that controlled conchoidal fracture was a "threshold" discovery (Isaac, 1976) among hominids that already possessed the sensorimotor and cognitive capacities for the full range of Oldowan technological performance. We might speculate about the behavioral context in which these capacities originally evolved, but there is no evidence that it included a more rudimentary, "pre-Oldowan," form of Mode I tool making.

The currently available record provides strong evidence for a lack of cumulative technological change prior to the appearance c. 1.6–1.7 Ma of Mode II shaping and more elaborate Mode I reduction strategies (Harris, 1978; de la Torre et al., 2003). This is consistent with Isaac's classic definition of the Oldowan Industrial Complex as "a set of generalized craft practices which had crossed a threshold formed by the discovery of conchoidal fracture," and constitutes a technological stasis (Semaw et al., 1997; Semaw, 2006) lasting from 2.6–1.6 Ma and characterized throughout by the least effort production of sharp edges (Toth, 1985). It is worth emphasizing that the word 'stasis' does not imply a lack of diversity but rather a state of equilibrium. Non-directional cultural variation in fine-grained technological strategies, though not currently evident, may eventually be identified within this equilibrium. Such a finding would perhaps be unsurprising given evidence of cultural variation in other tool making species (Whiten et al., 2001; Hunt and Gray, 2003) but would certainly be an important contribution to our understanding of hominid social organization and cognition (Stout, 2005). It is a separate question as to whether the creation of new archaeological taxa (e.g., Kibunjia, 1994) would be helpful in understanding this variation or would simply introduce a set of unstated culture-historic assumptions. Certainly such variation would not invalidate (Delagnes and Roche, 2005) the use of the term 'Oldowan' to describe the well-defined technological phenomenon manifest throughout Africa in the period from 2.6–1.6 Ma. As there is widespread agreement on the presence of Oldowan variation (e.g., Schick and Toth, 2006; Ludwig and Harris, 1998; Delagnes and Roche, 2005; de la Torre and Mora, 2005; Semaw, 2006; Stout and Semaw, 2006; Blumenschine et al., 2008; Braun and Hovers, 2009; Braun et al., 2009), future research should focus on its explanation. This will best be done by recognizing that cultural transmission and ecological adaptation are not mutually exclusive, and by combining the strengths of lithic reading and hominid behavioral ecology.

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Supplementary Online Material

Supplementary data associated with this article can be found in the online version, at appseca doi:10.1016/j.jhevol.2010.02.005.

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