Measuring the Complexity of Lithic Technology

by Charles Perreault, P. Jeffrey Brantingham, Steven L. Kuhn, Sarah Wurz, and Xing Gao

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Assessments of the complexity of lithic technologies coming from different time periods, regions, or hominid species are recurrent features of the literature on Paleolithic archaeology. Yet the notion of lithic complexity is often defined intuitively and qualitatively, which can easily lead to circular arguments and makes difficult the comparison of assemblages across different regions and time periods. Here we propose, in the spirit of Oswalt's techno-units, that the complexity of lithic technology can be quantified by counting the procedural units involved in tool manufacture. We define procedural units as mutually exclusive manufacturing steps that make a distinct contribution to the finished form of a technology. As a proof of concept, we use the procedural-unit approach to measure the complexity of 13 Paleolithic assemblages. While preliminary, these results provide a quantitative benchmark confirming that lithic technological complexity increased throughout the Paleolithic period. The method to measure lithic complexity outlined here will allow us to revisit several claims made about change in technological complexity during human evolution.

Introduction

Arguments about the complexity of lithic technologies coming from different time periods, regions, or hominid species are recurrent features of the literature on Paleolithic archaeology. Technological complexity—or technological "simplicity," "crudeness," "refinement," "sophistication," or "advancement"—are thought to have had important effects on forager populations, including broadening of ecological niches (Shea and Sisk 2010) or increasing the productivity and thereby aiding the dispersal of our species out of Africa (Mellars 2006*b*). Several processes can also drive changes in technological complexity. Studying changes in technological complexity thus allows us to make inferences about how these processes unfolded during human evolution. For instance, putative increases in technological complexity have been interpreted as signaling changes in cognitive abilities (e.g., Ambrose 2001, 2010; Coolidge and Wynn 2009; de Beaune 2004; Foley 1987; Foley and Lahr 2003; Haidle 2010; Mellars 1989, 2006*b*; Wadley 2010) as well as the extent to which our ancestors relied on social learning (Foley and Lahr 2003; Richerson and Boyd 2005). In line with theories of artifact design and technological organization—which predict that technological complexity will vary with factors such as prey choice, time budgeting, risk, labor costs, and mobility pattern (e.g., Bleed 1986; Bousman 1993; Kelly 1995; Osborne 1999; Oswalt 1976; Torrence 1983, 1989)—changes in lithic technology complexity have also been seen as a response to change in climate and environment (Mellars 1989, 2006*a*, 2006*b*; Shea and Sisk 2010), in variation in energetic constraints and time budgeting (Shea and Sisk 2010), in hunting strategies (Mellars 1989), or in lithic raw material quality (Brantingham et al. 2000; Mellars 2006*a*, 2006*b*; Pope 1989; Schick 1994). Cultural traditions or ethnic groups have also been interpreted as the cause of spatial variation in lithic complexity (Movius 1944, 1948; Schick 1994). Finally, there is even greater need for

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Charles Perreault is Assistant Professor in the Department of Anthropology at the University of Missouri, Columbia (107 Swallow Hall, Columbia, Missouri 65211, U.S.A. [perreaulc@missouri.edu]). **P. Jeffrey Brantingham** is Professor in the Department of Anthropology at the University of California, Los Angeles (341 Haines Hall, Box 951553, Los Angeles, California 90095, U.S.A. [branting@ucla.edu]). **Steven L. Kuhn** is Professor in the School of Anthropology at the University of Arizona (Emil W. Haury Building, P.O. Box 210030, Tucson, Arizona 85721, U.S.A. [skuhn@email.arizona.edu]). **Sarah Wurz** is Senior Researcher at the Institute for Human Evolution of the University of the Witwatersrand (Private Bag 3, PO WITS, 2050, Johannesburg, South Africa [sarah.wurz@wits.ac.za]). **Xing Gao** is Vice Director of the Institute of Vertebrate Paleontology and Paleoanthropology at the Chinese Academy of Sciences (P.O. Box 643, Beijing 100044, China [gaoxing@ivpp.ac.cn]). This paper was submitted 3 VII 13, accepted 18 VII 13, and electronically published 24 X 13.

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rigorous measures of technological complexity in order to test increasingly influential models linking demography and cultural evolution (Beatty 1995; Foley and Lahr 2003; Mellars 2006*a*; Powell, Shennan, and Thomas 2009; Premo and Kuhn 2010; Reiter 2000; Shennan 2001).

Consideration of technological complexity in the Paleolithic record is weakened, however, by a lack of explicit definition of complexity. Often one technology is simply described as more complex than another without explanation. Such intuitive notions of technological complexity are dangerous because they lead easily to circular arguments. For instance, methods such as prismatic blade technology have been assumed to be more complex that the Levallois method or bifacial shaping by the simple virtues of appearing later in time or being associated with modern humans (see Bar-Yosef and Kuhn 1999).

The complexity of Paleolithic technologies is also rarely quantified. Complexity is sometimes defined by the presence or absence of qualitative features, such as composite tools (Ambrose 2001, 2010; Coolidge and Wynn 2009), the use of compound adhesives (Wadley 2010), the use of a composite tool to make another composite tool (Lombard and Haidle 2012), or technologies that store energy exosomatically, such as the bow and arrow (Shea and Sisk 2010). But the usefulness of these qualitative definitions of technological complexity is limited because they are based on time-specific, region-specific, or culture-specific traits. They do not allow for the comparison of two assemblages if both either lack or possess these traits. In other words, if the transition from simple to complex technologies is marked by the advent of composite tools, then how does the complexity of two assemblages that lack composite tools compare? Finally, these qualitative definitions also fail to measure how much more complex these traits are. For instance, how much of a leap in technological complexity does the use of a composite tool really imply?

Given its importance in Paleolithic research, we have much to gain from developing a more objective way of measuring technological complexity that is quantitative and not bound to a specific time period, region, culture, or indeed any specific technology. We need a way to measure technological complexity that will allow us to detect an increase in complexity marked by, for example, the advent of composite tools but without treating composite tools as a qualitative break. Finally, our system of measurement should allow us to compare not just the complexity of different lithic assemblages but also of lithic and nonlithic technologies. We should be able to compare the complexity of Oldowan tools not only with that of European Upper Paleolithic blades but also with that of a Boeing 747.

Here we present a quantitative and widely applicable approach to measuring technological complexity in the archaeological record. We propose that technological complexity can be measured by counting the procedural units, or manufacturing "building blocks," represented in an assemblage. Below we describe this method, followed by its application to a series of Paleolithic assemblages as a proof of concept. Our goal here is not to test any specific hypothesis about the mechanisms driving changes in technological complexity but rather to develop a tool that can be used to test such hypotheses in a more rigorous manner than has been done so far.

Measuring Lithic Technology Complexity

We define technological complexity as the minimum amount of information that is needed to manufacture a product. This definition is in line with other formalized definitions of complexity (Shannon and Weaver 1949). Computer scientists, for example, have defined the complexity of an algorithm as the shortest string length, or the smallest number of bits of information, that is necessary to describe it (Chaitin 1970). This information criterion is analogous to the various measures of richness used to describe biological systems that are defined as the number of unique types of some constituent present within an aggregate group. For instance, at the level of the organism, biological complexity has been measured as the count of cell types (Bonner 1988). At the level of an ecosystem, biological complexity has been measured as the count of unique species it contains (Bonner 1988). Finally, the complexity of animal behavior has also been estimated by counting the number of elemental "building blocks" that is associated with a specific behavior or, at a larger scale, as the number of acts in a species' behavioral repertoire (Sambrook and Whiten 1997; Whiten et al. 1999).

In the same spirit, we argue that the complexity of a technology can be measured by counting the number of elemental building blocks associated with it. We call these building blocks "procedural units." We define procedural units as mutually exclusive manufacturing steps that make a distinct contribution to the finished form of the product of a technology. Focusing on lithic technology, the count of procedural units present in a tool reduction sequence is a measure of complexity because it reflects the minimum amount of information that is needed to carry it out to a successful end.

This procedural-unit approach to stone-tool complexity parallels Oswalt's "techno-units" (Oswalt 1976). Oswalt assessed the complexity of food-getting technologies by counting (1) the number of tool types present in a tool kit, which he called "subsistants," and (2) the number of integrated and physically distinct structures that contribute to the finished form of a tool, which he called "techno-units." Oswalt's method is powerful because it allows for the measurement of technological complexity cross-culturally. It has been applied to ethnographic data to test a wide range of hypotheses, including hypotheses about the ecological determinants of technological complexity (Collard, Kemery, and Banks 2005; Collard et al. 2011; Shott 1986; Torrence 1983, 1989, 2000) and the effect of demography on the evolution of technologies (Collard, Kemery, and Banks 2005; Collard et al. 2011; Kline and Boyd 2010; Oswalt 1976).

Oswalt (1976:229–230) recognized that there are problems with applying his concept of complexity to the archaeological record. First, the number of tool types present in a prehistoric tool kit is difficult to assess because the actual function of tools is difficult to infer. Moreover, when tool function can be determined, there is often overlap in the functional tasks accomplished with what appear to be morphologically distinct tool types. Second, the techno-unit approach will lead to underestimating the complexity of prehistoric technologies because of preservation biases. This is especially true for the Paleolithic record, were the range of preserved material is narrow. For instance, in most situations a complex technology such as the bow and arrow would leave in the archaeological record only one techno-unit, the stone projectile point. Yet with full preservation, it is clear that bow-and-arrow technologies are more complex technology than simple handheld scrapers, a 1-techno-unit technology. Attempting to infer what techno-units are missing in an archaeological assemblage for taphonomic reasons is not a solution because any given technology can contain a varying number of techno-units. For instance, Oswalt's data set (1976) contains examples of bows that range in complexity from 2 to 10 techno-units and of arrows that range from 2 to 13 techno-units. Finally, because Oswalt's approach focuses on the finished product, it fails to capture variation in the complexity involved in the making of different tools. For example, producing a prismatic blade can be more complex than making a digging stick, and yet both could be seen as simple, 1-techno-unit technologies when analyzed using Oswalt's method.

We can avoid to a certain extent these problems by focusing on the *chaînes opératoires* of technologies rather than on the finished products. Counting the procedural units present in a reduction sequence or in an assemblage allows us to avoid having to identify functionally distinct tool types as well as having to make inferences about tool parts that are missing from the assemblage. The idea of comparing technologies based on the number of manufacture steps they contain is not new (see, e.g., Ambrose 2001; Gowlett 1996) and is similar to the "cognigrams" method developed by Haidle (Haidle 2009, 2010; Lombard and Haidle 2012). Cognigrams can provide rich insights into the nature of technologies and human behaviors, but their value in comparative research is limited by the fact that they are not easily quantifiable.

Lithic Procedural Units

We have assembled a list of potential procedural units showing how the complexity of lithic technology can be measured. In accordance with our definition of procedural units, we have organized our list of lithic procedural units by reduction steps: preliminary treatment of raw material, core preparation techniques, blank production techniques, product shaping, and core rejuvenation. Such division is necessary because the same procedural unit, such as the use of a hard hammer, can serve distinct functions depending on the reduction step for which it is called into action. Each distinct usage should be counted as a different procedural unit. Conversely, the repeated use of a hard hammer within the same reduction step, such as in the shaping of a core, should not be counted as multiple independent procedural units; each hammer blow serves the same function, and the number of blows struck during the preparation of the core may vary from one core to another without it affecting the nature of the technology. This is analogous to Oswalt's (1976:52) recommendation that physically distinct elements serving the same purpose, such as the balls of a bola or the teeth of a rake, be counted as only one techno-unit. Researchers thus need to decide on a case-by-case basis whether the same procedural unit at different reduction steps constitutes functionally distinct manufacturing steps or not. Taking all these things into account and focusing on uncontroversial features that are commonly discussed in the lithic analysis literature, we have identified 35 procedural units that may be associated with lithic technology.

Preliminary Steps

(1) Raw material treatment: evidence of heat treatment

Core Preparation Techniques

(2) Decortification: cortex is removed

(3) Shaping of platform: platform intentionally prepared by flaking

(4) Shaping of flaking surface: face of flake removal is intentionally prepared by flaking

(5) Shaping of nonflaking surface: nonactive part of the core is shaped

(6) Blades: crested or *débordante* blades used to align face of flake removal

Core shaping techniques: (7) hard hammer percussion used, (8) soft hammer percussion used, (9) bipolar hammer percussion used, (10) indirect hammer percussion used, (11) pressure hammer percussion used, (12) pecking hammer percussion used

Blank Production Techniques

(13) Hard hammer percussion used

(14) Soft hammer percussion used

(15) Bipolar hammer percussion used

(16) Indirect hammer percussion used

(17) Pressure hammer percussion used

(18) Ochre applied (has traces of ochre)

Platform treatment: (19) abrasion (platform is rubbed/abraded), (20) overhang removal (small flakes are removed from core face adjacent to platform), (21) faceting (small flakes are removed from the platform)

Product Shaping

Edge shaping: (22) retouched edge (edge of final product is retouched)

Prehensile modification: (23) backing (a sharp era of final product is backed for manual prehension or hafting), (24) notching (final product is notched), (25) tanging (final product is tanged)

Surface shaping: (26) unifacial retouch (overall morphology of the blank altered by unifacial flaking), (27) bifacial retouch (overall morphology of the blank altered by bifacial flaking), (28) grinding (ventral/dorsal surface of the final product is ground)

(29) Bulbar thinning: flat flakes removed from bulbar face of the blank

Core Rejuvenation

(30) *Tablette*: platforms reshaped by removal of single large flakes

(31) *Outrepassée*: overpassed/plunging flakes struck intentionally to shape distal end of core

(32) *Débordante*: flakes or blades struck along edge of core to reshape the flaking surface

(33) Secondary crest: secondary crest used to reshape core face

(34) Rotation of core: subsequent flakes removed from nonopposed platforms

(35) Face shaping: core reshaped by lateral flaking between removals or series of removals

Using such a list, the complexity of *chaînes opératoires* can be translated into a number, the sum of procedural units present in the reduction sequence, that summarizes their complexity and that can be compared across cases.

The list above is by no means exhaustive. Lithic technology can potentially include more procedural units. For instance, in some archaeological contexts it might be useful to also count the use of binding material for composite tools as well as the type of binding material used (gum, ochre, fat, wax, resin). The list can also be extended to encompass within the same analysis other material and technologies, such as bone tools, ochre pigments, and shell beads.

In this regard, it is important to recognize that our unit of analysis is the procedural unit independent of its content. In that sense, it does not matter whether a core is shaped by a combination of hard hammer and indirect percussion or by a combination of hard and soft hammer: what matters is that in both cases, the shaping of the core involves two procedural units. This is analogous to what ecologists do when they contrast ecosystems by comparing their species richness, that is, the total count of species present in each ecosystem. This allows for ecosystems that have few or no species in common to be compared. Similarly, and similar to Oswalt's techno-units, the count of procedural units provides us with a common measurement unit that allows for the comparison of different technologies. This is also why the list above cannot be used as a universal checklist: whether or not an item on the list constitutes a procedural unit really depends on whether it constitutes a mutually exclusive manufacturing step that makes a distinct contribution to the finished form of the product of a particular technology. It is this focus on the definition of a procedural unit rather than on its content that allows for comparison among a wide range of lithic and nonlithic technologies across cultures, time, space, and species.

Many aspects of the way procedural units are counted depend on the research question asked, such as whether idiosyncratic units, or units that contribute to the decorative aspects of a technology, should be included or excluded from the analysis. There is no single set of units that applies universally, so it is important that these decisions be reported in publications in order to increase the replicability of analyses and to facilitate the comparison of published results. Finally, the analysis of technological complexity can be conducted at different scales because the procedural-unit approach can be used to measure the complexity of individual *chaînes opératoires* as well as that of assemblages as a whole. This flexibility is useful because there are many archaeological contexts in which *chaînes opératoires* cannot be easily reconstructed.

Proof of Concept

We have conducted a series of experiments to evaluate the validity of the procedural-unit approach to lithic technology by measuring the complexity of 13 lithic assemblages. More specifically, we are interested in detecting a temporal trend in lithic complexity through the Paleolithic period. We have purposely tried to sample assemblages coming from a wide range of time periods and spatial locations. Our sample thus includes sites dating from the Lower Paleolithic (Early Stone Age) to the Upper Paleolithic (Late Stone Age) and ranging from South Africa to Turkey. Given the temporal and spatial range it covers, our sample is too small to draw any definitive conclusion about patterns of complexity during the Paleolithic period. However, it is a useful proof of concept for the procedural-unit approach because it shows that (1) the method can capture variation in lithic complexity and (2) the method is sufficiently robust in the face of variation in how procedural units are defined.

Different analysts may count procedural units in a lithic assemblage differently. To examine this problem, we simulated the noise that could be generated by different analysts with different views on what constitutes a procedural unit by lumping and splitting the list presented above. In other words, we ask to what extent does the temporal pattern of lithic complexity that we can observe in the Paleolithic record depend on whether the assemblages have been analyzed by a "splitter" or by a "lumper." More saliently, what if a mixture of "lumpers" and "splitters" analyzed the assemblages compared, as would be the case in a data set assembled from various publications? To answer these questions, we counted the procedural units of the 13 Paleolithic assemblages using two different lists. First, the assemblages were analyzed using the extended list presented above. In our view, this is the list that best captures what we mean by procedural units in the context of lithic technology. Second, we produced a second estimate of the complexity of the assemblages using a shorter version of the above list. This second estimate represents how a conservative lithic analyst who prefers to err on the side of caution might count procedural units. It excludes nine variables that may be deemed ambiguous and too difficult to identify, such as heat treatment of raw material or the rotation of the core during core rejuvenation. It also lumps 14 procedural units into four units. For instance, it lumps together hard hammer, soft hammer, indirect, and pressure flaking into a single category: "unipolar percussion." This "conservative" list contains a total of 16 procedural units as opposed to 38 procedural units for the "nonconservative" list.

Table 1 summarizes our sample of assemblages as well as their complexity relative to the two lists (see supplementary material, available online, for details). The counts of procedural units are reported for assemblages as a whole rather than for individual *chaînes opératoires*. These counts thus represent the complexity of the tool kits used by the populations that produced these assemblages rather than the complexity of specific tools they used. Table 1 shows that the procedural-unit approach does capture variation in the complexity of lithic technologies. Using the conservative list, the counts of procedural units range from four, with the Lower Paleolithic assemblage of Tabun Cave in Israel, to 11, with the Middle Stone Age assemblage of Klasies River Mouth in South Africa. With the nonconservative list, the counts of procedural units range from six, with the two Oldowan assemblages, to 23, with the Mousterian assemblage of Amud Cave.

Figure 1 shows the count of procedural units of the assemblages plotted against the midpoint of their age on a log-log scale (the two Oldowan assemblages, A.L. 894 and A.L. 666, are plotted against their *terminus ante quem* date, >2.35 mya). A linear regression analysis in which the dependent variable is the logarithm of the count of procedural units and the independent variable is the logarithm of the midpoint of the age of the assemblage suggests that the complexity of lithic technologies increases steadily through time. The slope β of the best-fit linear model for the nonconservative count of procedural units is -0.314 ($P < .001$), which means that the size of the procedural-unit inventory shrinks by about 3% as the age of the material increases by 10%. The model explains 68% of the variance (adjusted $R^2 = 0.68$). The relationship between age and lithic complexity is also detectable when the conservative view of procedural units is adopted, although it is not as strong: $\beta = -0.184$ (a decrease in complexity of about 2% per 10% increase in age; $P < .005$, adjusted $R^2 = 0.49$). These results suggest that the temporal pattern of increase in complexity of lithic technology through time is strong enough to be detected by both conservative lumpers and nonconservative splitters. But what if both conservative and nonconservative estimates were combined in the same analysis? To test this possibility, we created 1,000 data sets by selecting randomly, for each assemblage, a count of procedural units from the conservative or the nonconservative view. Each data set thus contains a different mixture of conservative and nonconservative analytical decisions simulating the effect of operator variation on estimates of lithic complexity. Running linear regression analysis on these data sets, we find that the results are affected by this sampling procedure but not so profoundly as to disguise the basic patterning. The effect size of age on the count of procedural units across these 1,000 regression analyses ranges from -0.11 to -0.38 with an average of -0.25, and the adjusted R^2's of these different linear models range from 0.13 to 0.73 with an average of 0.39 (fig. 2).

Although there is a general increase in lithic technological complexity over the Pleistocene, the rate of increase in complexity is greater for the subset of Middle Paleolithic and Middle Stone Age assemblages ($n = 8$; see fig. 3). The slope of the best-fit linear model is steeper ($\beta = -0.46$ and -0.7, $P = .004$ and 0.003 for the conservative and nonconservative counts, respectively), and the variance explained by the model is greater (adjusted $R^2 = 0.74$ and 0.88, respectively). This suggests that the increase in lithic complexity within the Middle Stone Age/Middle Paleolithic might have been more regular than it is across the whole Paleolithic period (thus better described by a linear model on a log-log scale). This result contrasts with other studies that have found no general technological trends within the Middle Paleolithic period (see de la Torre 2013; Kuhn 2013). Assuming that this long-term trend for increasing complexity through time holds as more assemblages are added to our sample, this analysis is in line with the view that behavioral complexity increased gradually and cumulatively through the Middle Paleolithic/Middle Stone Age and well before 50 ka (e.g., Brown et al. 2009; d'Errico and Henshilwood 2007; d'Errico et al. 2005; Marean et al. 2007; McBrearty and Brooks 2000).

Overall, our analysis suggests that trends such as the increase of lithic complexity through the Paleolithic period may be detected in a robust manner even in the face of divergence between analysts in the definition of procedural units. Even though our results are preliminary, we find it intriguing that the complexity of these lithic assemblages align along the same trend line even though they were produced over thousands of years by different hominid species coming from various parts of Africa and Eurasia and given the presumed sensitivity of lithic technology to environmental, demographic, behavioral, economical, and cognitive factors.

Discussion and Conclusion

Our main argument in this paper is that the complexity of lithic technology can be measured by counting the procedural units, that is, the mutually exclusive manufacturing steps that contribute to the finished form of the technology. Because it is quantitative and independent of any specific technology, time period, region, or culture, this approach can also be applied to nonlithic technologies and could help solve many of the issues associated with previous attempts at measuring

Table 1. Count of procedural units of 13 Paleolithic assemblages

Assemblage	Period	Age	Count of procedural units: Conservative list	Count of procedural units: Nonconservative list	References
A.L. 894, Ethiopia	Lower Paleolithic (Oldowan)	>2.35 mya	5	6	Hovers 2009*a*; E. Hovers and A. Davidszon, unpublished manuscript
A.L. 666, Ethiopia	Lower Paleolithic (Oldowan)	>2.35 mya	5	6	E. Hovers and A. Davidszon, unpublished manuscript; Kimbel et al. 1996
GnJh-03, Kenya	Early Stone Age (Acheulean)	ca. 500–284 ka	8	14	Cornelissen 1992; Leakey et al. 1969; McBrearty 1999; Tryon, McBrearty, and Texier 2005
Tabun Cave, Unit XI-XIV, Israel	Early Paleolithic	ca. 450–225 ka	4	7	
Yanmburgaz Cave, Turkey	Early Middle Paleolithic	275 ka	6	7	Kuhn, Arsebük, and Howell 1996
Tabun Cave, Unit IX, Israel	Early Middle Paleolithic (Mousterian)	ca. 225–100 ka	6	13	R. Shimelmitz and S. L. Kuhn, unpublished manuscript
GhJh-74, Kenya	Middle Stone Age	ca. 200 ka	5	11	Tryon 2003, 2006
Klasies River Mouth, Klasies stage, South Africa	Middle Stone Age	115–100 ka	9	19	Wurz 2002*a*, 2002*b*
Qafzeh Cave (layers XXIV-III), Israel	Middle Paleolithic (Mousterian)	92 ka	10	19	Hovers 2009*b*; Hovers and Raveh 2000
Klasies River Mouth, Mossel Bay stage, South Africa	Middle Stone Age	100–80 ka	9	15	Wurz 2002*a*, 2002*b*
Amud Cave B4-B1, Israel	Middle Paleolithic (Mousterian)	68–55 ka	11	23	Alperson-Afil and Hovers 2005; Ekshtain 2006; Goder 1997; Hovers 1998, 2007; Hovers et al. 2011
Klasies River Mouth, Howieson Poort stage, South Africa	Middle Stone Age	62–58 ka	9	22	Wurz 2002*a*, 2002*b*
Üçağızlı Cave, Ahmarian layers B, B1-3, C, Turkey	Upper Paleolithic	ca. 35–32 ka	9	15	Kuhn et al. 2009

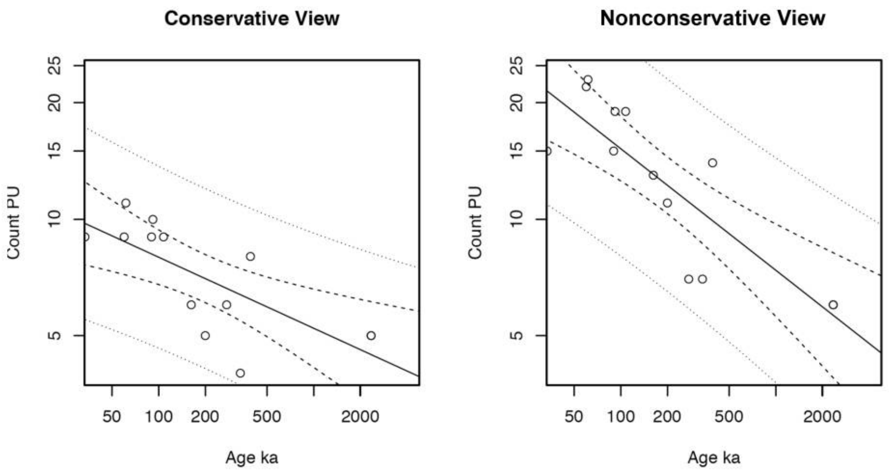

Figure 1. "Conservative" and "nonconservative" count of procedural units for 13 Paleolithic assemblages (see table 1) plotted against their age. Note the logarithmic scale (base 10) on both axes. Assemblages with a range of ages are plotted against the midpoint of the age range. The line represents the best-fit linear model using least squares regression (conservative: $\beta = -.184$, standard error [SE] = 0.05, $P = .005$, $n = 13$, adjusted $R^2 = 0.49$; nonconservative: $B = \beta = -.314$, SE = 0.06, $P = .0003$, $n = 13$, adjusted $R^2 = 0.68$). The dashed lines represent the 95% confidence bands, and the dotted lines represent the 95% prediction bands.

complexity in the archaeological record. As such, this method will allow us to revisit several claims about the complexity of Paleolithic technologies. For instance, do Clark's technological modes really represent an increase in complexity (Foley and Lahr 2003)? Are Upper Paleolithic tools more complex than Middle Paleolithic ones (Mellars 1989), or is the Levallois method more complex than the production of blades from prismatic cores (Bar-Yosef and Kuhn 1999)? Our preliminary analysis suggests the existence of a long-term trend toward greater complexity in the evolution of lithic technologies throughout the Paleolithic period but that there is a particularly sharp increase in complexity within the Middle Paleolithic and the Middle Stone Age. A larger sample of assemblages will allow us to verify this finding and compare the long-term rates of change in technological complexity between Europe, Africa, and Asia as well as between different periods of the Paleolithic.

Nonetheless, there are several caveats to the procedural-unit approach. For instance, it fails to capture some aspects of what is commonly meant by "technological complexity," such as the level of skills involved in the manufacturing of tools or the complexity that emerges from the hierarchical organization of some manufacturing procedures (Byrne 2007). A second caveat is that the procedural-unit approach is not completely impervious to taphonomic issues. For instance, the complexity of lithic technologies could plateau at

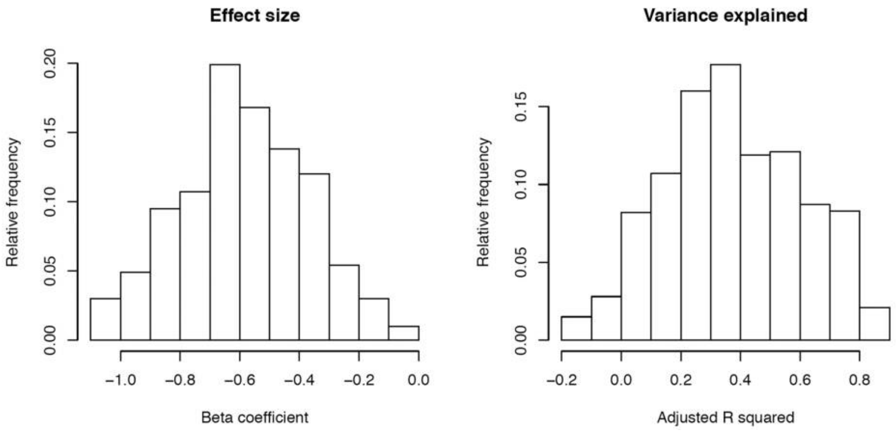

Figure 2. Relative frequency histogram of the effect size and variance explained of the best-fit linear model using least squares regression calculated over 1,000 data sets generated by randomly selecting for each of the 13 assemblages either the conservative or the nonconservative count of procedural units (see table 1).

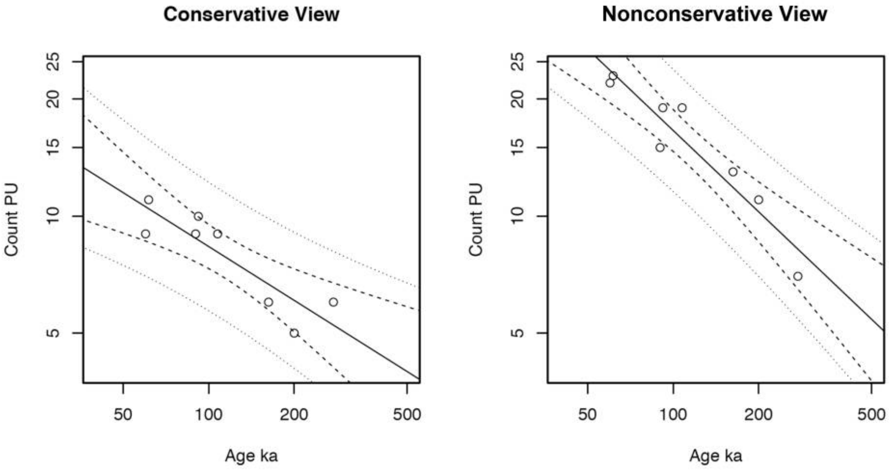

Figure 3. "Conservative" and "nonconservative" count of procedural units for eight Middle Paleolithic/Middle Stone Age assemblages plotted against their age. Note the logarithmic scale (base 10) on both axes. Assemblages with a range of ages are plotted against the midpoint of the age range. The line represents the best-fit linear model using least squares regression (conservative: $\beta = -.46$, standard error [SE] $= 0.1$, $P = .004$, $n = 8$, adjusted $R^2 = 0.74$; nonconservative: $B = \beta = -.70$, SE $= 0.1$, $P = .0003$, $n = 13$, adjusted $R^2 = 0.88$). The dashed lines represent the 95% confidence bands, and the dotted lines represent the 95% prediction bands.

certain points in time while the complexity of other technological parts made of perishable material may continue to increase. This means that the procedural-unit approach can be biased by false negatives and as such provides us only with a lower bound for technological complexity. Moreover, different classes of material, such as lithic and ceramic, can also be subject to different taphonomic processes and therefore be less amenable to comparison. And like other measures of richness in the archaeological record (e.g., Cannon 2001; Cochrane 2003; Meltzer, Leonard, and Stratton 1992; Rhode 1988), the count of procedural units is likely dependent on sample size.

Another source of problems is the effect of subjective inferences on the count of procedural units. Some procedural units are harder than others to identify in an archaeological assemblage, and not every analyst will be comfortable with the inferential leap required to mark them as "present"—the use of a soft hammer versus indirect percussion comes to mind here. Other operator errors can affect the replicability of the method, such as disagreement between operators on whether something like rotating the core during core rejuvenation constitutes a procedural unit or not. As such, the procedural-unit approach to lithic complexity suffers from the same kinds of subjectivity that prevail in lithic analysis in general.

Our proof-of-concept study, however, does provide tentative evidence that the method is sufficiently robust to subjectivity in the definition of lithic procedural units. We were able to detect a temporal trend in the complexity of Paleolithic lithic technology even when the list of procedural units examined was reduced by 54%. Even though the procedural units discussed in this paper are uncontroversial and frequently discussed in the archaeological literature, it would be useful to verify the reliability of the approach by measuring the level of agreement between different operators and experimental context. But the problem of subjectivity can also be addressed statistically. By analyzing large samples we can average out the noise created by factors that are independent of the variable of interest, such as operator errors, between-operator disagreements, or differential preservation. This is not an attempt to avoid the issue of subjectivity in defining procedural units. On the contrary, the problem of noise in empirical data is not specific to the procedural-unit approach: it is a problem that every scientific discipline faces, and the most powerful way we have to deal with it is to collect larger samples. The standard error of the mean, $S_{\bar{x}} = s/\sqrt{n}$, where s is the standard deviation of the sample and n the size of the sample, is a good measure of the effect of errors on the mean of a sample.[1] Because the standard error of the mean decreases in proportion to the square root of sample size, for any given amount of error in a sample there will always be a sample size that is large enough to estimate accurately the

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[1] In an ideal and purely mechanistic world, $y = x$, where y is the variable of interest (e.g., lithic complexity) and x is the predictor (e.g., the age of assemblages). But we live in a world where $y = x + \varepsilon$, where ε is the noise in the data. In most cases this error will be random with respect to x; some of us will tend to overestimate the number of procedural units present in assemblages while others will tend to underestimate it. The standard error of the mean, a measure of the effects of errors on the mean of a sample, is used to calculate the confidence interval within which the true mean of a population lies. For example, if the average complexity in a sample of Middle Stone Age assemblages of size n is x with a standard deviation of s, then there is a 95% chance that the true mean complexity in the Middle Stone Age lies within the interval defined by $x \pm 1.96(s/\sqrt{n})$.

true mean complexity of a sample. The same line of reasoning can be extended to regression analysis. In sum, the influence of operator errors can be dealt with statistically. This allows for the procedural-unit approach to remain a useful metric by which the complexity of prehistoric technologies can be quantified and compared and to test a wide range of hypotheses about what drives changes in technological complexity.

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References Cited

Alperson-Afil, N., and Erella Hovers. 2005. Differential use of space at the Neandertal site of Amud Cave, Israel. *Eurasian Prehistory* 3:3–22.

Ambrose, Stanley H. 2001. Paleolithic technology and human evolution. *Science* 291(5509):1748–1753.

———. 2010. Coevolution of composite-tool technology, constructive memory, and language. *Current Anthropology* 51(suppl. 1):S135–S147.

Bar-Yosef, O., and S. L. Kuhn. 1999. The big deal about blades: laminar technologies and human evolution. *American Anthropologist* 101(2):322–338.

Beatty, J. 1995. The evolutionary contingency thesis. In *Concepts, theories, and rationality in the biological sciences*. G. Wolters and J. G. Lennox, eds. Pp. 45–81. Pittsburgh, PA: University of Pittsburgh Press.

Bleed, Peter. 1986. The optimal design of hunting weapons: maintainability or reliability. *American Antiquity* 51(4):737–747.

Bonner, John Tyler. 1988. *The evolution of complexity by means of natural selection*. Princeton, NJ: Princeton University Press.

Bousman, C. Britt. 1993. Hunter-gatherer adaptations, economic risk and tool design. *Lithic Technology* 18(1/2):59–86.

Brantingham, P. Jeffrey, John W. Olsen, Jason A. Rech, and Andrei I. Krivoshapkin. 2000. Raw material quality and prepared core technologies in northeast Asia. *Journal of Archaeological Science* 27(3):255–271.

Brown, Kyle S., Curtis W. Marean, Andy I. R. Herries, Zenobia Jacobs, Chantal Tribolo, David Braun, David L. Roberts, Michael C. Meyers, and Jocelyn Bernatchez. 2009. Fire as an engineering tool of early modern humans. *Science* 325(5942):859–862.

Byrne, R. W. 2007. Culture in great apes: using intricate complexity in feeding skills to trace the evolutionary origin of human technical prowess. *Philosophical Transactions of the Royal Society* B 362(1480):577–585.

Cannon, Michael D. 2001. Archaeofaunal relative abundance, sample size, and statistical methods. *Journal of Archaeological Science* 28(2):185–195.

Chaitin, G. J. 1970. On the difficulty of computations. *IEEE Transactions on Information Theory* IT-16:5–9.

Cochrane, Grant W. G. 2003. Artefact attribute richness and sample size adequacy. *Journal of Archaeological Science* 30(7):837–848.

Collard, Mark, Briggs Buchanan, Jesse Morin, and Andre Costopoulos. 2011. What drives the evolution of hunter-gatherer subsistence technology? a reanalysis of the risk hypothesis with data from the Pacific Northwest *Philosophical Transactions of the Royal Society* B 366(1567):1129–1138.

Collard, Mark, Michael Kemery, and Samantha Banks. 2005. Causes of toolkit variation among hunter-gatherers: a test of four competing hypotheses. *Canadian Journal of Archaeology* 29:1–19.

Coolidge, Frederick L., and Thomas Wynn. 2009. *The rise of* Homo sapiens*: the evolution of modern thinking*. Malden, MA: Wiley-Blackwell.

Cornelissen, E. 1992. *Site GnJh-17 and its implications for the archaeology of the Middle Kapthurin Formation, Baringo, Kenya*, vol. 133 of *Annales, sciences humaines*. Tervuren: Musée Royale de l'Afrique Centrale.

de Beaune, Sophie A. 2004. The invention of technology: prehistory and cognition. *Current Anthropology* 45(2):139–162.

de la Torre, Ignacio, Jorge Martínez-Moreno, and Rafael Mora. 2013. Change and stasis in the Iberian Middle Paleolithic: considerations on the significance of Mousterian technological variability. *Current Anthropology* 54(suppl. 8):S320–S336.

d'Errico, Francesco, and Christopher Henshilwood. 2007. Additional evidence for bone technology in the southern African Middle Stone Age. *Journal of Human Evolution* 52(2):142–163.

d'Errico, Francesco, Christopher Henshilwood, Marian Vanhaeren, and Karen van Niekerk. 2005. *Nassarius kraussianus* shell beads from Blombos Cave: evidence for symbolic behaviour in the Middle Stone Age. *Journal of Human Evolution* 48(1):3–24.

Ekshtain, R. 2006. *A comparative study of knapping accidents in the Levantine Mousterian*. Jerusalem: Hebrew University of Jerusalem.

Foley, Robert. 1987. *Another unique species*. New York: Longman Scientific & Technical.

Foley, Robert, and Marta Mirazón Lahr. 2003. On stony ground: lithic technology, human evolution, and the emergence of culture. *Evolutionary Anthropology: Issues, News, and Reviews* 12(3):109–122.

Goder, M. 1997. Technological and typological aspects of Layer B1 in the Late Mousterian site at Amud Cave. MA thesis, Hebrew University of Jerusalem.

Gowlett, John. 1996. The frameworks of early hominid social systems: how many useful parameters of archaeological evidence can we isolate? In *The archaeology of human ancestry: power, sex and tradition*. J. Steele and S. Shennan, eds. Pp. 135–183. London: Routledge.

Haidle, Miriam Noël. 2009. How to think a simple spear. In *Cognitive archaeology and human evolution*. S. de Beaune, F. L. Coolidge, and T. Wynn, eds. Pp. 57–73. Cambridge: Cambridge University Press.

———. 2010. Working-memory capacity and the evolution of modern cognitive potential. *Current Anthropology* 51(suppl. 1):S149–S166.

Hovers, Erella. 1998. The lithic assemblages of Amud Cave: implications for the end of the Mousterian in the Levant. In *Neanderthals and modern humans in Western Asia*. T. Akazawa, K. Aoki, and O. Bar-Yosef, eds. Pp. 143–163. New York: Plenum.

———. 2007. The many faces of cores-on-flakes: a perspective from the Levantine Mousterian. In *Cores or tools? alternative approaches to stone tool analysis*. S. P. McPherron, ed. Pp. 42–74. Cambridge: Cambridge Scholars.

———. 2009*a*. Learning from mistakes: flaking accidents and knapping skills in the assemblage of A. L. 894 (Hadar, Ethiopia). In *The cutting edge: new approaches to the archaeology of human origins*. K. Schick and N. Toth, eds. Pp. 137–150. Gosport, IN: Stone Age Institute.

———. 2009*b*. *The lithic assemblages of Qafzeh Cave*. New York: Oxford University Press.

Hovers, Erella, A. Malinsky-Buler, M. Goder-Goldberger, and R. Ekshtain. 2011. Capturing a moment: identifying short-lived activity locations in Amud Cave, Israel. In *The Lower and Middle Palaeolithic in the Middle East and neighbouring regions*. J.-M. Le Tensorer, R. Jagher, and M. Otte, eds. Pp. 110–114. Liège: University of Liège Press.

Hovers, Erella, and A. Raveh. 2000. The use of a multivariate display technique in the analysis of inter-assemblage lithic variability: a case study from Qafzeh Cave, Israel. *Journal of Archaeological Science* 27(11):1023–1038.

Kelly, Robert L. 1995. *The foraging spectrum: diversity in hunter-gatherer lifeways*. Washington, DC: Smithsonian Institution.

Kimbel, W. H., R. C. Walter, D. C. Johanson, K. E. Reed, J. E. Aronson, Z. Assefa, C. W. Marean, et al. 1996. Late Pliocene *Homo* and Oldowan stone tools from the Hadar Formation (Kada Hadar Member), Ethiopia. *Journal of Human Evolution* 31:549–561.

Kline, Michelle A., and Robert Boyd. 2010. Population size predicts technological complexity in Oceania. *Proceedings of the Royal Society* B 277 (1693):2559–2564.

Kuhn, Steven L. 2013. Roots of the Middle Paleolithic in Eurasia. *Current Anthropology* 54(suppl. 8):S255–S268.

Kuhn, Steven L., Güven Arsebük, and F. Clark Howell. 1996. The Middle Pleistocene lithic assemblage from Yarimburgaz Cave, Turkey. *Paléorient* 22(1):31–49.

Kuhn, Steven L., Mary C. Stiner, Güleç Erksin, Ismail Özer, Hakan Yılmaz, Ismail Baykara, Ayşen Açıkkol, et al. 2009. The Early Upper Paleolithic occupations at Üçağızlı Cave (Hatay, Turkey). *Journal of Human Evolution* 56:87–113.

Leakey, M., P. V. Tobias, J. E. Martyn, and R. E. F. Leakey. 1969. An Acheulian industry with prepared core technique and the discovery of a contemporary hominid mandible at Lake Baringo, Kenya. *Proceedings of the Prehistoric Society* 3:48–76.

Lombard, Marlize, and Miriam Noël Haidle. 2012. Thinking a bow-and-arrow set: cognitive implications of Middle Stone Age bow and stone-tipped arrow technology. *Cambridge Archaeological Journal* 22(2):237–264.

Marean, C. W., Miryam Bar-Matthews, Jocelyn Bernatchez, Eric Fisher, Paul Goldberg, Andy I. R. Herries, Zenobia Jacobs, et al. 2007. Early human use of marine resources and pigment in South Africa during the Middle Pleistocene. *Nature* 449(7164):905–908.

McBrearty, Sally. 1999. The archaeology of the Kapthurin Formation. In *Late Cenozoic environments and hominid evolution: a tribute to Bill Bishop.* P. Andrews and P. Banham, eds. Pp. 143–156. London: Geological Society.

McBrearty, Sally, and Alison S. Brooks. 2000. The revolution that wasn't: a new interpretation of the origin of modern human behavior. *Journal of Human Evolution* 39(5):453–563.

Mellars, Paul. 1989. Technological changes across the Middle-Upper Palaeolithic transition: economic, social and cognitive perspectives. In *The human revolution: behavioural and biological perspectives on the origins of modern humans.* P. Mellars and C. Stringer, eds. Pp. 339–365. Princeton, NJ: Princeton University Press.

———. 2006*a*. Going east: new genetic and archaeological perspectives on the modern human colonization of Eurasia. *Science* 313(5788):796–800.

———. 2006*b*. Why did modern human populations disperse from Africa ca. 60,000 years ago? a new model. *Proceedings of the National Academy of Sciences, U.S.A.* 103(45):9381–9386.

Meltzer, David J., Robert D. Leonard, and Susan K. Stratton. 1992. The relationship between sample size and diversity in archaeological assemblages. *Journal of Archaeological Science* 19(4):375–387.

Movius, Hallam, L. 1944. *Early man and Pleistocene stratigraphy in southern and eastern Asia*. Papers of the Peabody Museum of Archaeology and Ethnology, vol. 19. Cambridge, MA: Peabody Museum of American Archaeology and Ethnology.

———. 1948. The Lower Paleolithic cultures of southern and eastern Asia. *Transactions of the American Philosophical Society* 38:329–420.

Osborne, A. J. 1999. From global models to regional patterns: possible determinants of Folsom hunting weapon design diversity and complexity. In *Folsom lithic technology: explorations in structure and variation.* D. S. Amick, ed. Pp. 188–213. Ann Arbor, MI: International Monographs in Prehistory.

Oswalt, Wendell H. 1976. *An anthropological analysis of food-getting technology.* New York: Wiley-Interscience.

Pope, G. G. 1989. Bamboo and human evolution. *Natural History* 10:48–57.

Powell, Adam, Stephen Shennan, and Mark G. Thomas. 2009. Late Pleistocene demography and the appearance of modern human behavior. *Science* 324(5932):1298–1301.

Premo, L. S., and Steven L. Kuhn. 2010. Modeling effects of local extinctions on culture change and diversity in the Paleolithic. *PLoS ONE* 5(12):e15582.

Reiter, Paul. 2000. From Shakespeare to Defoe: malaria in England in the Little Ice Age. *Emerging Infection Diseases* 6(1):1–11.

Rhode, David. 1988. Measurement of archaeological diversity and the sample-size effect. *American Antiquity* 53(4):708–716.

Richerson, Peter J., and Robert Boyd. 2005. *Not by genes alone: how culture transformed human evolution.* Chicago: University of Chicago Press.

Sambrook, T., and A. Whiten. 1997. On the nature of complexity in cognitive and behavioural science. *Theory and Psychology* 7(2):191–213.

Schick, Kathy D. 1994. The Movius Line reconsidered: perspectives on the earlier Paleolithic of eastern Asia. In *Integrative paths to the past: paleoanthropological advances in honor of F. Clark Howell.* R. S. Corruccini and R. L. Ciochon, eds. Pp. 569–596. Englewood Cliffs, NJ: Prentice Hall.

Shannon, C. E., and W. Weaver. 1949. *The mathematical theory of communication.* Urbana: University of Illinois Press.

Shea, John J., and Matthew L. Sisk. 2010. Complex projectile technology and *Homo sapiens* dispersal into western Eurasia. *Paleoanthropology* (2010):100–122.

Shennan, S. 2001. Demography and cultural innovation: a model and its implications for the emergence of modern human culture. *Cambridge Archaeological Journal* 11(1):5–16.

Shott, Michael J. 1986. Technological organization and settlement mobility: an ethnographic examination. *Journal of Anthropological Research* 42:15–51.

Torrence, R. 1983. Time budgeting and hunter-gatherer technology. In *Hunter-gatherer economy in prehistory: a European perspective.* G. Bailey, ed. Pp. 11–22. Cambridge: Cambridge University Press.

Torrence, Robin. 1989. Re-tooling: towards a behavioral theory of stone tools. In *Time, energy and stone tools.* R. Torrence, ed. Pp. 57–66. Cambridge: Cambridge University Press.

———. 2000. Hunter-gatherer technology: macro- and microscale approaches. In *Hunter-gatherers: an interdisciplinary perspective.* C. Panter-Brick, R. H. Layton, and P. Rowley-Conwy, eds. Pp. 99–143. Cambridge: Cambridge University Press.

Tryon, Christian A. 2003. The Acheulian to Middle Stone Age transition: tephrostratigraphic context for archaeological change in the Kapthurin Formation. PhD dissertation, University of Connecticut, Storrs.

———. 2006. "Early" Middle Stone Age lithic technology of the Kapthurin Formation (Kenya). *Current Anthropology* 47:367–375.

Tryon, Christian A., Sally McBrearty, and P. J. Texier. 2005. Levallois lithic technology from the Kapthurin Formation, Kenya: Acheulian origin and Middle Stone Age diversity. *African Archaeological Review* 22(4):199–229.

Wadley, Lyn. 2010. Compound-adhesive manufacture as a behavioral proxy for complex cognition in the Middle Stone Age. *Current Anthropology* 51(suppl. 1):S111–S119.

Whiten, A., J. Goodall, W. C. McGrew, T. Nishida, V. Reynolds, Y. Sugiyama, C. E. G. Tutin, R. W. Wrangham, and C. Boesch. 1999. Cultures in chimpanzees. *Nature* 399(6737):682–685.

Wurz, Sarah. 2002*a*. The Middle Stone Age sequence at Klasies River, South Africa. PhD dissertation, University of Stellenbosch.

———. 2002*b*. Variability in the Middle Stone Age lithic sequence, 115,000–60,000 years ago at Klasies River, South Africa. *Journal of Archaeological Science* 29(9):1001–1015.