Special Issue: Reduction Sequence, *Chaîne Opératoire*, and Other Methods: The Epistemologies of Different Approaches to Lithic Analysis

Continuous Modeling of Core Reduction: Lessons from Refitting Cores from WHS 623x, an Upper Paleolithic Site in Jordan

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ABSTRACT

The systematic production of usable flakes is often presented by lithic technologists as a rigid set of strategies or procedures to be followed in a step-by-step fashion. The quintessential example is the *chaîne opératoire,* developed by the French in the 1980s and widely applied today. An alternate view is that lithic reduction is a fluid behavioral set conditioned by an intimate familiarity with techniques and materials and tempered by environmental and situational circumstances. In an effort to address the 'how' and 'why' questions central to an epistemologically informed archaeology, and thus help lithic analysts from different research traditions better understand one another, we contrast models of discrete lithic reduction stages with those based on models of reduction continua. How we understand reduction influences how we interpret it. First, we summarize experimental data from North American bifacial reductions that can be modeled as continuous reduction processes using regression and principal components analyses. Then we apply these same methods to refitted cores from WHS 623x, an Upper Paleolithic site in west-central Jordan. The analysis shows that some aspects of lithic reduction are best modeled as continua, while others are better modeled as discrete. If reduction is continuous in some respects, it should be understood in continuous terms in those respects.

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Many archaeologists view lithic reduction as a process that unfolds in essentially discrete, generalizable stages (e.g., Boëda 1993; Boëda et al. 1990; Callahan 1979). This view has a long history and can be traced to various sources. In the Old World, with its great time depth, it is often tied to assumptions and preconceptions about hominin cognitive evolution, with the implication that biology and culture are linked in a more or less linear fashion (e.g., Grahame Clark 1969, Foley and Lahr 1994), and that lithic typology and technology tend to co-vary with one another over space and time (e.g., Bar-Yosef 1994, 2002; Bordes 1961; de Sonneville and Perrot 1953). In the New World, William Henry Holmes originated the reduction-sequence concept over a century ago (Holmes 1894; Shott 2003). But the possibility that reduction might be continuous in some cases and respects, shaped only by generalizable contingencies with which all Stone Age societies must contend, has seldom been addressed. Holmes apparently shared this view. He explicitly recognized that stages were analytical constructs, not revealed entities present in the minds of people long dead:

> "There can really be no line of demarcation separating the phenomena of one stage from those of another and there is a danger of the change being thought of as a definite and restricted episode, as marking a complete ending of one phase of existence, and as being a datum point from which to begin the study of the succeeding phase" (Holmes 1892: 248–249, cited in Meltzer and Dunnell 1992: xxix).

The stage concept thus assumes stages to be valid and replicable, defined by legitimate patterns of association among variables, categorical and continuous, and that every ar-

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chaeologist who contemplates the same specimens would inductively arrive at the same number of stages possessed of the same characteristics. Unfortunately, both assumptions are questionable, as recent studies have shown (e.g., Bisson 2000; Bradbury and Carr 1999; Ingbar et al. 1989; Monnier 2006; Shott 1996).

Callahan's (1979) Paleoindian bifacial reduction sequence, legitimately celebrated both for its great detail and the beauty of its illustrations, is a good example. Like most archaeologists, Callahan viewed bifacial reduction in sequential terms, although he spoke also of continua. Indeed, Callahan established the vocabulary that endures today—Paleoindian archaeologists routinely speak of 'Stage 2' or 'Stage 3' bifaces. In so doing, they employ Callahan's concepts and terms.[1] But Ingbar and colleagues (1989) showed that reduction is at least as well understood as a continuum, not a sequence of discrete stages. They accomplished this by showing how flake debris ordered by removal from cores varied not so much by stage—all in this or that stage being very similar or identical in variables that defined the stage—but continuously. In the process, they demonstrated that removal order was a linear or log-linear function of several continuous attributes of flakes (see also Bradbury and Carr 1999; Clark 1976; Shott 1996; Henry 2003).

Callahan's stages were defined by metric and categorical properties of preforms themselves, not the debris struck from them. Yet the validity of the stage concept also can be tested against preform data because Callahan (1979) reported weight and the basic dimensions of length, width and thickness by reduction stages. He defined from six to nine stages by inextricable combinations of ratio-scale variables like length and width, and nominal- and ordinal-scale technological and inferred behavioral variables (e.g., section form, pattern of flake scars). Callahan reported data only for specimens in Stages 1–4, reasonable enough since subsequent stages differed little in size from 'Stage 4' preforms and more in the details of fluting. Therefore, we consider only Stages 1–4.

When defined by combinations of categorical and continuous variables, Callahan's stages may well be valid. But their distinctiveness and internal integrity in continuous variables is undemonstrated. Mean values by stage certainly differ—no surprise since stages were defined partly by size, measured by continuous variables. But differences in mean dimensions appear to be more an artifact of analysis than a property of stages themselves. A ratio scaled variable with a natural zero point and independent of the measurement unit, stature in adult males is a continuous variable best described in continuous terms. However, except for a loss of precision (hence information), nothing about the distribution of stature in a sample of men precludes defining it on an ordinal scale (e.g., in terms of types or stages—short, medium and tall). But unless specified on legitimate grounds (e.g., a tri-modal distribution), boundaries between such types are arbitrary, and calculating mean stature per type reveals little about the underlying continuous distribution of the variable (Clark 1982). More insidious, perhaps, is the tendency for the resulting classes to become reified and reproduced in peoples' minds and analyses, as if they were in some sense 'real.' There are no 'types' of stature, but rather continuous variation in the variable 'stature,' limited only by measurement precision. Any type so defined may possess some descriptive value, but it is neither an efficient, precise, nor particularly useful way to portray variation, and it might misrepresent its nature.

If reduction stages are valid analytically, then they should differ among themselves but the specimens assigned to them should not. Stages are defined by sets of objects, elements, or attributes that are essentially identical with respect to the stages' defining characteristics. This proposition is easily tested using Callahan's biface data. Stages were subdivided into two equal or approximately equal halves by weight. Substages of Stages 1 (n=4 in first substage, n=5 in second) and 3 (n=10 in first substage, n=8 in second because of tied cases at the boundary value between substages) were slightly unequal. As expected, weight differed between substages that, like the larger stages, arbitrarily divide a continuum of variation. But width differed significantly between each stage's substages, length in all cases except Stage 1, and thickness in Stage 3. Therefore, metric differences *within* Callahan's stages were as great as those *between* them.

Consider a view of size variation in Callahan's preforms that does not assume categorical stages of reduction. Principal-components analysis (PCA) using length, width, thickness, and weight yielded a single significant component (PC1) that explained 74% of the variance in the data. The component clearly is a measure of size because all variables loaded highly on it. Among stages, weight always correlated most strongly with component score, width usually was ranked second; length and thickness correlated more weakly and not always significantly. Preform width-thickness ratio, a shape measure Callahan considered important in distinguishing stages, correlated with PC1 only in Stages 3 and 4, suggesting that shape and size co-vary most strongly at advanced reduction stages as a preform began to approximate its final 'ideal' form. This seems reasonable on technological grounds because reduction begins with cores that naturally vary quite a lot, continues with flake blanks that vary considerably, and culminates in finished tools that, owing to size, technological and functional constraints, vary less. Weight is perhaps the best summary measure of size among the original variables, further demonstrating that the component measures size because weight is a summary size measure. Mean component scores by Callahan stage are about equally spaced, each separated from bracketing stages by values of about 0.60.

Figure 1 plots weight against the size component. Of course the variables are strongly correlated, because weight contributed to the component's definition more than any other primary variable. Figure 1 shows that there is a continuous relationship between the variables, and considerable overlap in range between specimens at different stages. Size, measured either by weight or the principal component, varies continuously, not by discrete stages.

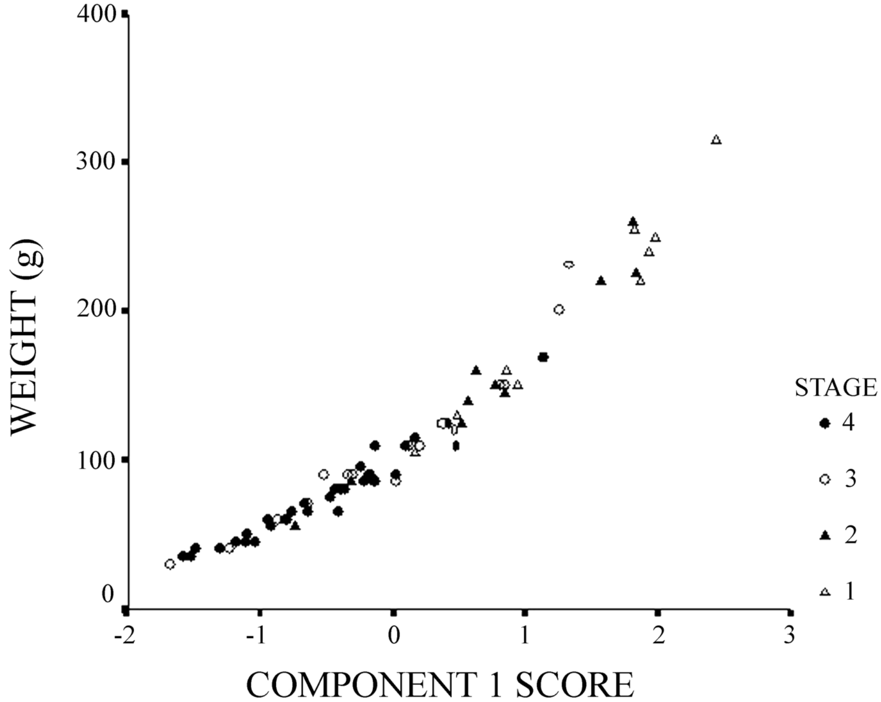

Figure 1. Continuous distribution of weight upon PC1 in Callahan's (1979) biface reductions.

Stages do not separate in the plot. Instead they lack compositional integrity because each overlaps considerably with the one(s) preceding and following it. For example, some 'Stage 1' specimens have lower values on both variables (i.e., are smaller) than many 'Stage 2' and even some 'Stage 3' specimens. Quadratic regression nicely describes the relationship (r^2=.98), linear regression only slightly less so (r^2 =.94). Regression is a measure of the strength of association between or among variables. It assesses the strength of the statistical relationship between a random variable and one or more independent variables used to predict the value of the random variable. In metric dimensions and weight, Callahan's biface stages arbitrarily parse a continuum of variation.

Despite occasional acknowledgment of some of these problems, North American archaeologists continue to routinely assign Paleoindian preforms to one or another of Callahan's stages. If stage assignments are valid and can be generalized, then dimensions and weight by stage should not differ between assemblages. Discriminant analysis, a multivariate technique that maximizes the difference between *a priori* groups, is another way to gauge the validity of the stage concept. It assumes discrete classes (stages in this context), multivariate normal distributions of variables that define each class, and equal covariance matrices between groups (Baxter 1994: 185–191; Clark 1980: 40–44; Shott 1997: 90). The first assumption is valid for this test, the second is irrelevant for descriptive purposes (Baxter 1994: 188), and the method is not particularly sensitive to the third (Baxter 1994: 199). Callahan's stages are suitable for discriminant analysis. They are thought to be distinct, they are comprehensive (i.e., there are no other groups but Stages 1–4), and they are—arguably—considered equally homogeneous, hence "of a similar geometrical size and shape in multivariate space" (Baxter 1994: 188) although, as noted above, earlier stages are likely to be more variable than later ones.

Analysis involved simultaneous variable entry (of preform length, width, thickness, and weight), equal prior probabilities and within-group covariance matrices, measures justified in Shott (1997: 90–92). Fisher's linear discriminant analysis in SPSS yielded a single eigenvector greater than 1.0 that explained 91% of the variance in Callahan's preform data. Classification functions, very similar between stages, are given in Table 1, classification results in Table 2. Overall, only 68% of preforms were classified correctly, and only half or little more in Stages 1–3. In Stages 1, 2 and 4, specimens are apportioned among three predicted stages; Stage 3 specimens are distributed in all predicted stages. On variables analyzed, preforms are difficult to distinguish by stage. Instead, variation among and between 'stages' appears to be continuous.

None of this is to criticize Callahan, nor replication experiments generally. The data and understanding they provide are valuable. Nor does it prove that bifacial reduction is continuous, not discrete or sequential, in all respects and cases. Callahan's model includes categorical as well as continuous variables (1979: 30, 31). Perhaps categorical variables sort strictly or associate significantly by stage. In the fine details of fluting, which occurred after Callahan's Stage 4, the sequence may better describe the process than does continuous variation. Perhaps continuous variables

TABLE 1. CLASSIFICATION FUNCTIONS FOR CALLAHAN'S PREFORM STAGES.

Stage 1 = 0.53*length + 0.84*width + 2.95*thickness – 0.33*weight
Stage 2 = 0.53*length + 0.84*width + 3.23*thickness – 0.36*weight
Stage 3 = 0.52*length + 0.82*width + 2.87*thickness – 0.36*weight
Stage 4 = 0.52*length + 0.82*width + 2.87*thickness – 0.36*weight

sort or associate by stage in other experiments. But in Callahan's experiments, which rightly have influenced a generation of archaeologists, much variation described as discrete and sequential is continuous. Nor is Callahan responsible for the (generally reasonable) use that others have made of his model. But if what Callahan and other archaeologists classify as the same stage differs significantly in size variables, then stage assignments are not as valid or replicable as they are thought to be. This does not mean that other archaeologists' assignments of preforms to Callahan stages necessarily are invalid, only that assignments should not be taken at face value.

Nor is this passage a pedantic digression that belabors a small point. How we understand bifacial reduction influences how we interpret it. If reduction is continuous in some respects, it should be understood in continuous terms. Analysis demonstrates as much in tools (e.g., Dibble 1995), as did earlier studies cited above in the debris produced by reduction. Standard descriptions of reduction sequences do not always distinguish the sequences considered characteristic of particular cultures or phases, and technology can vary independently from typology (e.g., Clark 2002a,b; Marks 1983; Sackett 1988). Quantitative models of reduction continua (e.g., regressions) might, at least in some respects, better distinguish the technological practices of different technological traditions, assuming that the latter exist and can be detected by archaeologists (see, e.g., Clark [2002a] for a critique of traditions in 'deep time') and that they in fact differ. For instance, *rate of weight or size reduction* may vary substantially between traditions or sequences the nearer one gets to the finished product. Differences in the size ratio of blank to finished tool might distinguish others. Debris-size distributions, of considerable theoretical and analytical value (Shott 1994), might differ as well.

Finally, Old World scholars might not realize that almost all the experimental work in North America is directed at reconstructing the bifacial technologies used to manufacture Paleoindian and Archaic projectile points. Although we argue that parts of the continuum model also will be relevant for understanding non-bifacial knapping technologies, clearly it is not applicable to all of them. For example, some aspects of blade technology do not produce débitage that corresponds to the predictions generated from biface replication. Dorsal scar count is not positively correlated with removal order in the sequence, as it is in bifacial technologies, nor is the extent of cortex inversely correlated with the number of blade detachments (Tostevin, pers. comm.).

INFERRING REDUCTION SEQUENCE CHARACTERISTICS

Inference to reduction sequence is routine in lithic analysis world-wide, and many studies schematically depict the sequences revealed by analysis (e.g., de Bie and Caspar 2000; Gowlett 1996; Marks 1983). Yet there are no rigorous methods for inferring reduction sequences, nor—in deep time—consensus about what they might mean behaviorally. Instead, archaeologists combine evidence from experimental replications, refit chains, preforms broken or discarded at various reduction 'stages,' kinds and amounts of flake debris, and the morphometrics of finished tools to reconstruct reduction sequences. It makes good sense to do this—to use many sources of evidence—and most archaeologists probably would agree with at least the major aspects of most reconstructed sequences. But the absence of clear analytical standards—what evidence is to be used, and how—inevitably produces disagreement (e.g., Clark and Riel-Salvatore 2006).

To acknowledge disagreements is not to dispute all inferences or to question the validity of any of them. Indeed, if lithic reduction was patterned not only by custom or tradition but also by raw material and circumstance, then differing views are correct for different assemblages. But the absence of fixed standards advises constructive skepticism toward inferences of reduction sequence.

In particular, stage approaches beg several questions.

TABLE 2. CLASSIFICATION RESULTS FOR CALLAHAN'S PREFORM STAGES.

Stage	Actual Count	Predicted Count by Stage				Classification Rate
		1	2	3	4	
1	9	5	3	1	0	5/9=55%
2	10	3	5	0	2	5/10=50%
3	18	2	3	9	4	9/18=50%
4	34	1	0	4	29	29/34=85%

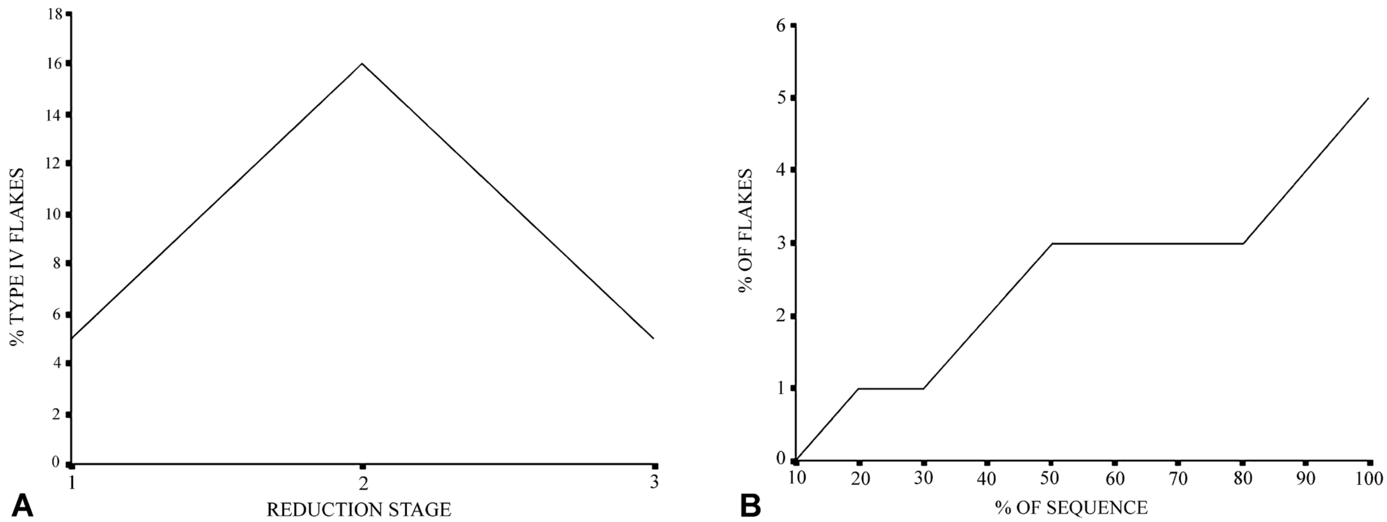

Figure 2. 'Type IV' flakes by a) inferred reduction stage, and b) percentage of sequence completed (from Bradley and Sampson 1986).

How many stages exist in a sequence? How is each defined? How are stages distinguished from one another and where exactly do borders lie between them? Obviously, the number of stages is an empirical matter, since different sequences need not involve the same number (although many workers, particularly in the Old World research traditions, assume that the number of stages can be generalized [Clark and Riel-Salvatore 2006]). A problem arises, however, when archaeologists recognize different numbers of stages in the same sequence. Inevitably, such ambiguity extends to the distinction between stages. For example, the number, meaning, and distinction between Newcomer's (1971: Figure 13) Acheulean handaxe stages are not clear, nor do they square with those of Gowlett (1996), Ashton et al. (1998), or McPherron (2003). Stages often are defined by the percentage of cortex cover on flake exterior surfaces, and archaeologists tend to assume that cortex cover declines monotonically during reduction. Leaving aside the notoriously difficult problem of how to measure it (see Dibble et al. [2005] for a recent effort to improve cortex measurement), in one study cortex persisted until nearly the end of reduction and most ordinal scale measures of cortex cover did not sort out as the successive stage models predicted they would (Shott 1996: Figure 3). Neither did platform types covary as assumed with reduction stage models (Shott 1996: 11).

Not only are stages ambiguous, they also conceal important variation. For instance, Bradley and Sampson's (1986) impressive replication study of Acheulean bifaces needlessly assumed reduction by stages. Their 'Type IV' bifacial thinning flake (1986: Figure 2.3) peaked in abundance in the second of three handaxe reduction stages (Figure 2a). Plotting frequency against percentage of the sequence completed (1986: Figure 2.8) showed that this flake type regularly increased in frequency from the start of reduction until its end. Figure 2b more faithfully represents the nature of this process than do the stages shown in Figure 2a. Bradley and Sampson (1986) unintentionally concealed this pattern because the stages they defined did not cover equal segments of the reduction sequence.

Despite problems, the stage concept might be valid in some cases, although its validity tends more often to be assumed than demonstrated analytically. There is no doubt that qualitative changes can occur in reduction (e.g., with a change in hammer or a shift from reducing a core for the purpose of shaping it to the purpose of producing flakes from it). Certainly the change from percussion to pressure flaking introduces differences of kind as well as degree. But we should show that this actually occurred, not assume it *a priori*. As the starting point in any reduction analysis, we should entertain the null hypothesis that reduction can be modeled as a continuous process (Shott 1994: 83).

CONTINUOUS BIFACE-REDUCTION MODELS

Ingbar and colleagues (1989) pioneered this approach in bifacial reduction by expressing flakes numbered by removal order as a linear function of metric variables. Five regression equations that express the removal order of flakes from cores as functions of various flake attributes are given in Table 3. Naturally, these studies differed in important ways. Ingbar et al. (1989) scaled exterior facets to flake area and Bradbury and Carr (1999) to flake weight, both better than Shott's (1996) simple facet count. Shott measured flake weight, probably a better size indicator than the other two (Pelcin 1996). Others used $\log_e$ transformation, Ingbar et al. perhaps $\log_{10}$ transformation. Ingbar and colleagues (1989: 126) reported several results, preferring their Model 5 for its slope coefficient exceeding 1.0. However, their Model 4 had a considerably higher r^2 and, as they noted, is the simplest. Shott (1996: 17) reported results for both conjoined and originally intact flakes, others only for the latter. Bradbury and Carr (1999) analyzed multiple and diverse reduction sequences and extended the approach to resharpening debris, although the formula in Table 3 is specific to their

TABLE 3. REGRESSION MODELS OF THE REDUCTION CONTINUUM.

Equation	r^2	Source
removal order = (-12.14*log thickness) + (9.65*log scar density) (Model 4)	.94	Ingbar et al. 1989: 126
removal order = (-63.75*log thickness) + (18.24*log scar density) + (29.62*log area) (Model 5)	.50	Ingbar et al. 1989: 126
removal order = (12.1 * scar count) - (15.5*log$_e$weight) + (4.9*platform width)	.82	Shott 1996: 17
removal order = (10.0 * scar count) - (15.3*log$_e$weight) + 17.0*platform width)	.78	Shott 1996: 17
% removal = (.09*platform facets) + (.07*log$_e$width) + (.16*log$_e$scargrams[1])	.86	Bradbury and Carr 1999

[1]scargrams = exterior facets/weight.

bifacial reduction experiments. Most importantly, they used a relative measure of reduction rather than Ingbar's or Shott's number in removal order. This is a definite improvement since we cannot know in archaeological assemblages the number of flakes produced in individual sequences (except in the extremely unusual case of completely refitted cores). Despite the methodological differences, all sources identified faceting and size as correlates of removal order, and all successfully modeled bifacial reduction as a continuous process.

The stage view can be questioned not only in the experimental studies cited above but in empirical ones as well (Shott 2004). In particular, flake refit chains reveal the order in which flakes were removed from cores or tools. Few empirical chains are lengthy, let alone complete, but some contain sufficient numbers of refits that they can be used to test the continuum view of reduction. Unfortunately, few refitting sources reported dimensions of each flake.

One that did is Roebroeks's (1988: Table 7, Figure 55) report on about 30 flakes refitted to Core Bv 1527 (Schlanger's [1996] 'Marjorie's Core') from the Dutch early Middle Paleolithic Maastricht-Belvédère assemblage, dated to OIS 7 (247–190 kya). Roebroek's data did not include the variables necessary to test the continuous models cited above. Using the data he does report, it is apparent in Figure 3 that removal order from this core is not a simple function of flake size or number of dorsal facets, perhaps because highly prepared Levallois cores do not necessarily follow the same reduction process as do other cores. Yet flakes from late prehistoric North American core refit chains do exhibit continuous variation as a function of removal order (Shott 2004: 226).

Ultimately, there is no substitute for much more experimental data that can gauge the effects of raw material, core size and form, hammer type, and number and nature of desired flakes upon the products of core reduction. What-

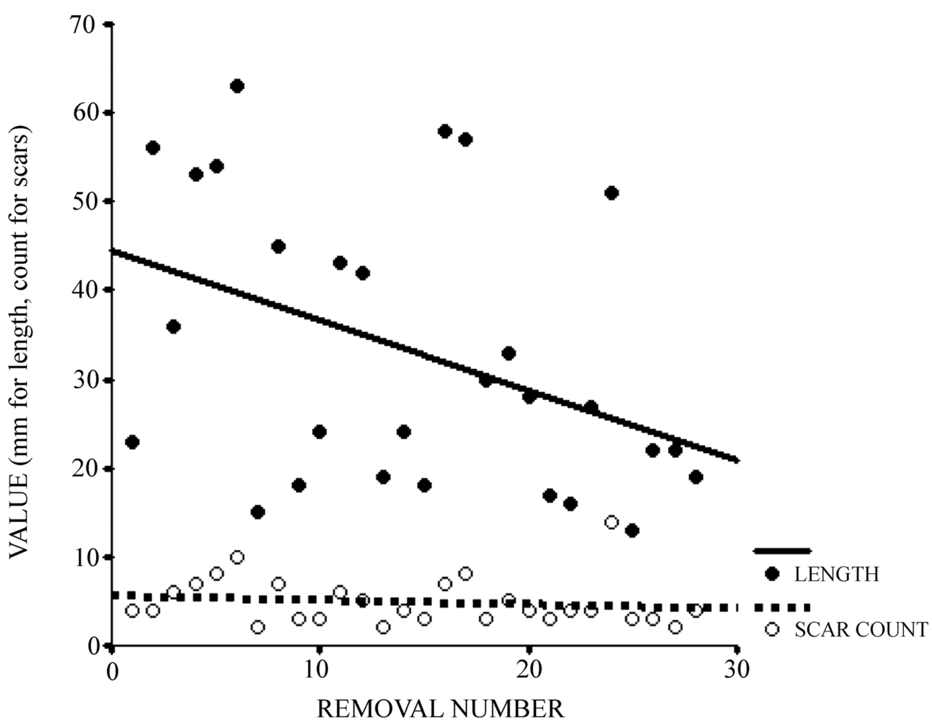

Figure 3. Flake length and scar count by removal number from core Bv 1527 (from Roebroeks 1988: Table 7, Figure 55).

ever the technological approaches taken in those studies, it is vital that analysts also measure the resulting flakes both for thoroughness in principle and because continuous models can only be fit using continuous data. This does not mean that analysts must abandon the typological approaches that many of them prefer, merely that they must supplement their typological assignments with measurements and observations made on each flake. Until such a body of experimental data exists, there is no choice but to use whatever data are at hand, particularly in the form of refit chains assembled from archaeological assemblages. We take that approach here. In the process, we choose a particularly challenging case of blade-core reduction that differs in many obvious ways (some qualitative) from the bifacial-core reduction models discussed above. If any part of blade-core reduction can be understood in continuous terms, this finding recommends the general search for not just stage-based or qualitative dimensions of the reduction process, but continuous ones as well.

TABLE 4. WHS 623x
ARTIFACT FREQUENECIES BY CLASS.*

Artifact Class	Total		Refitted	
	N	%	N	%
Exhausted Core	7	1.2	7	3.6
Core Platform Flake	15	2.6	15	7.7
Flake (>2cm)	151	26.4	71	36.2
Flake (<2cm)	114	19.9	-	-
Blade (>3cm)	196	34.2	103	52.6
Bladelet (<3cm)	61	10.6	-	-
Subtotal:	573	100.0	196	100.0
Debris:	312		-	-

*from Lindly et al. 2000: 213

WADI HASA SURVEY SITE 623X

Site 623x was a very dense lithic scatter of only 3m^2 located in marl deposits on a small knoll at the edge of what was Pleistocene Lake Hasa in west-central Jordan (Figure 4). The site was discovered during the 1984 field season of the Wadi Hasa Paleolithic Project directed by Clark (Clark et al. 1987). WHS 623x lies at 815masl on the south bank of the wadi between two Middle Paleolithic sites but is itself classified as Upper Paleolithic (Ahmarian). Based on radiocarbon dates from nearby Ahmarian sites reported by Coinman (2003: 151–170), it probably dates to c. 26–23 kya. WHS 623x appears to be but “a moment frozen in time” (Coinman and Clark 2000: 6) where hominins reduced 11–12 flint cores, picked through the resulting blades, selected those they wanted, and abandoned the rest (Lindly et al. 2000: 211–226). The potential for reconstructing the core reduction sequences at the site was immediately apparent.

A grid of eight 50 x 50cm units was laid out over the site. Every artifact on the surface was collected and bagged by unit. Units were excavated to a depth of 5cm below datum; all sediment was screened through 4mm mesh. The underlying marl became extremely consolidated below c. 5cm, and no artifacts were recovered below that level. After initial field processing, the collection was shipped to Arizona State University for analysis. As refitting occurred, it became clear that several cores of different materials could be reconstructed. Eventually, the collection included refit chains from 11 core reductions, accounting for 196 artifacts (34.2%) of the 885 pieces recovered. The average number of conjoined flakes on each core is 18, ranging from 5 to 39 blanks. Earlier studies (Beck 1986; Lindly 1987; Lindly et al. 2000) described the 623x assemblage and compared it to the celebrated refit chains from the Middle/Upper Paleolithic transition site of Boker Tachtit, in the central Negev highlands (Volkman 1983). Our purpose here is narrower. We examine metric data from 623x flakes to determine how they pattern with removal order.

DATA AND ANALYSIS

Beck (1986) and Lindly (1987) originally described and analyzed the 623x assemblage. They also conducted technological analysis along several lines, partly by comparing 623x to Boker Tachtit. Among other things, they defined two basic core types (single-platform and opposed-platform) and variants of each knapped to produce only blades or blades and flakes. Lindly’s exhaustive refitting is the focus of our work. He refitted 34.2% of the total assemblage, a rate that compares favorably to other cases. For refitting flakes to cores or to other flakes, as at 623x, rates between 5–20% seem common (Cahen et al. 1979: 663; Cziesla 1990: Tables 1, 2; Pigeot 1987: 13; Seeman et al. 1994: 11). Blades and other flakes (we call them ‘flakes’ generically here) from the various cores were refitted to one another and to the cores. Most refitted flakes originated from the same platform, although some from opposed-platform cores originated from the second platform (in one case, from a third). Artifact frequencies from 623x are given in Table 4.

Lindly (1987) coded all flakes in refit chains for many metric and technological variables. Among them we emphasize those listed in Table 5. Length, width, and thickness are basic flake dimensions, measured as described in Lindly et al. (2000: 215, 216). Flake area is approximated as the simple product of length and width, elongation as the quotient of length to width. Platform area is the product of the two original platform dimensions. Scar count is simply the number of scars or facets (>5 sq. mm) from previous removals visible on the exterior flake surface. Exterior platform angle is formed between the platform surface and the exterior surface. It was measured by goniometer at the thickest part of the platform and the exterior of the object, as near the striking axis as possible. As discussed above, these variables were useful in earlier studies of continuous reduction models. In addition, basic dimensions, flake area and perhaps platform area are size measures, elongation a shape measure derived from the conventional definition of blades as flakes whose axial length exceeds twice their

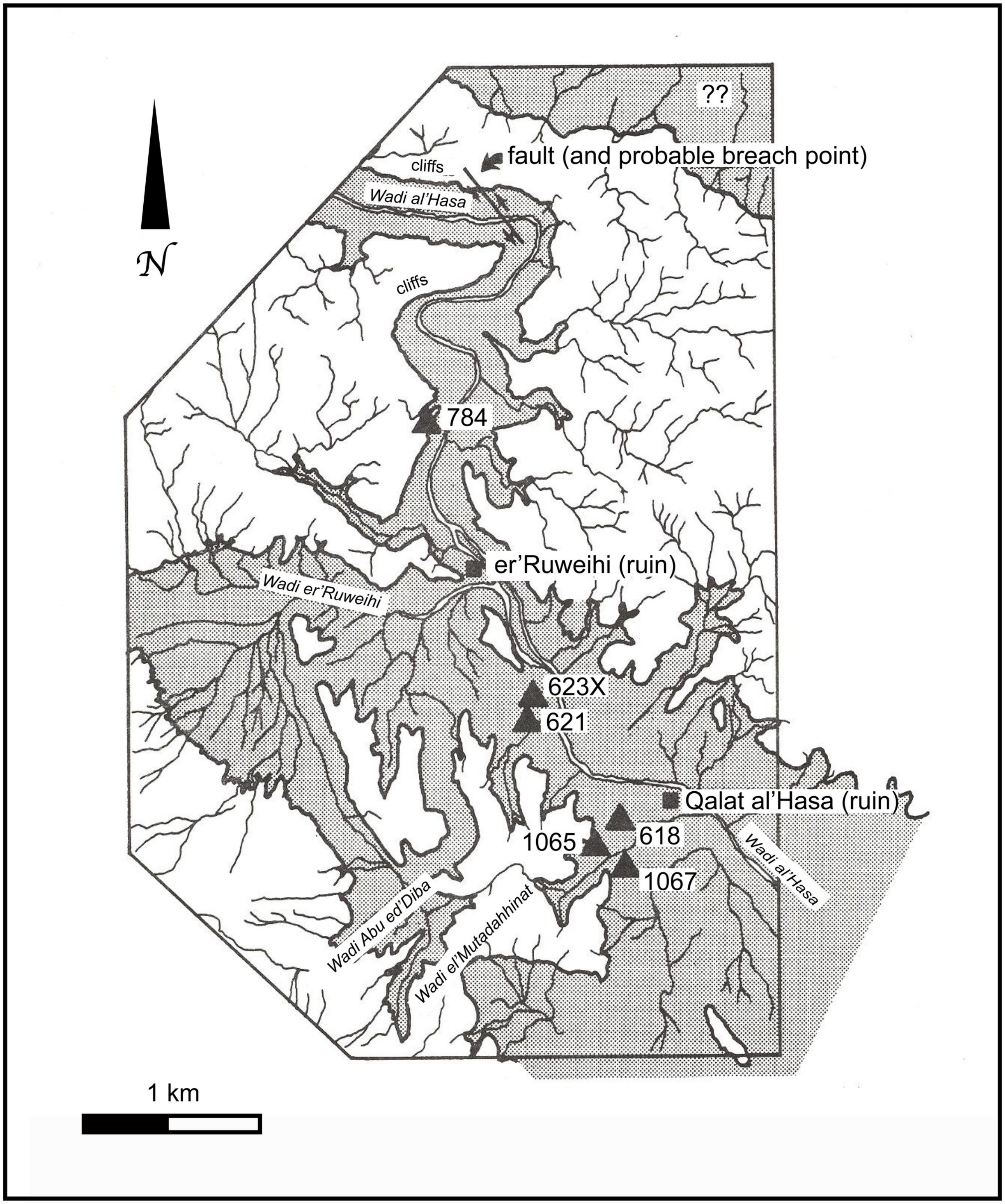

Figure 4. Location of WHS 623x in the Wadi al-Hasa Region, Jordan. The map shows the northwest end of Paleolake Hasa with the maximum former extent of the lake determined by plotting the tops of the lacustrine marls (from Clark 1984: 211, 241).

width. In several controlled experiments, platform area declined and exterior platform angle and scar count increased with reduction (e.g., Davis and Shea 1999; Pelcin 1996; Shott et al. 2000). Therefore, these variables are sensitive to reduction and may pattern with it in archaeological data.

Beck (1986) and Lindly (1987; Lindly et al. 2000) explored some of the implications of 623x's refit chains and compared them with those from other Levantine Middle

TABLE 5. ANALYTICAL VARIABLES FOR WHS 623x FLAKES.

Original Variables	Derived Variables
Length (cm)	Flake area (length x width)
Width (cm)	Elongation (length / width)
Thickness (cm)	Platform area (plat. width x plat. thick.)
Platform width (cm)	
Platform thickness (cm)	
Exterior-surface scar count	
Exterior platform angle (°)	

and Upper Paleolithic sites. They reveal important aspects of form and technology (e.g., the demonstration from refitting >180 cores from Boker Tachtit that technology and typology did not co-vary with one another in any direct way [Marks and Kaufman 1983; Volkman 1983], as they are often assumed to do by many Old World workers [Clark 1991: 85–88]). In one respect, though, refitting data at this site and others remains underexploited. Flake-refit chains conclusively illustrate at least relative, and sometimes interval, order of flake removal from tools or cores. Chains should be analyzed for the relationship between flake metrics and removal order.

Our use of these data must be qualified in three ways. First, many blades and other flakes struck from 623x cores were carried away from the site. As a result, refit chains are lengthy but not complete. Their tight refitting makes it clear that some flakes were removed in sequence such that, say, numbers 9, 10 and 11 from a core were struck in three successive blows. But there are gaps separating other numbered flakes (e.g., Figure 5) formed by unknown numbers of flakes that the knappers retained. Second, except for platform preparation flakes struck before the first blade removal, we cannot know if the flake bearing the lowest index number was the first one struck as opposed, say, to the third or seventh, the possible earlier ones having been retained by the knapper and carried away from the site for use elsewhere. As a result, removal order as determined by refitting is an ordinal (not interval) scale variable that preserves only the relative order of, but not necessarily the interval between, removals. Flake 9 in any refit chain was struck before Flake 10 was, but we cannot always know if it was struck immediately before. Nor is Flake 9 necessarily the ninth flake struck. Third, most flakes are broken, and intact specimens from refit chains are too few for valid analysis. Therefore, we combine intact and broken flakes, even though some original and derived variables are minimum values. For what it is worth, there is no difference in mean length (t=1.53, p=.13) between broken and intact flakes, although there are significant differences in the number of dorsal scars (t=2.25, p=.03) between them. In both cases, broken specimens have *higher* average values. We acknowledge these limitations as unavoidable consequences of the empirical data.

Obviously, refit chains imperfectly preserve information about the nature and extent of reduction sequences. The varying number and nature of reductions carried out in studies cited earlier produced significant differences not only in statistical results but in salient properties (e.g., material, core size and form, knapping methods, and desired products) and the magnitude of their effects. What is more, all the previously cited studies involved core reduction to produce bifaces, not blades, thus a broad type of reduction that may have been more common in the New World than the Old. Collectively, the small body of relevant work demonstrates that at least some reductions can be modeled as continua. But they are too few, the range of technological and other variation they encompass too limited, for general application.

Moreover, the value of such models depends upon their use. As descriptions of sets or populations of flakes struck from cores, regression models document the continuous distribution of at least metric dimensions and the con-

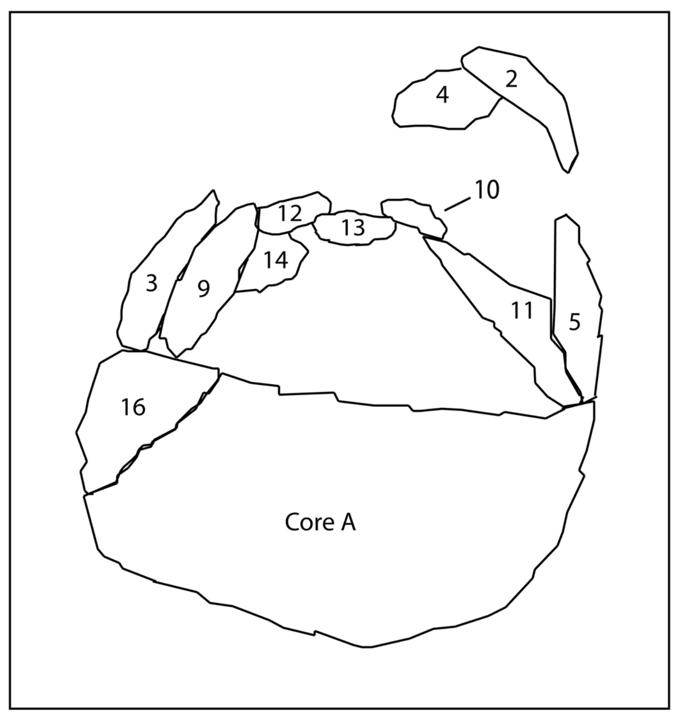

Figure 5. WHS 623x Core A refit chain diagram (from Lindly et al. 2000: 218).

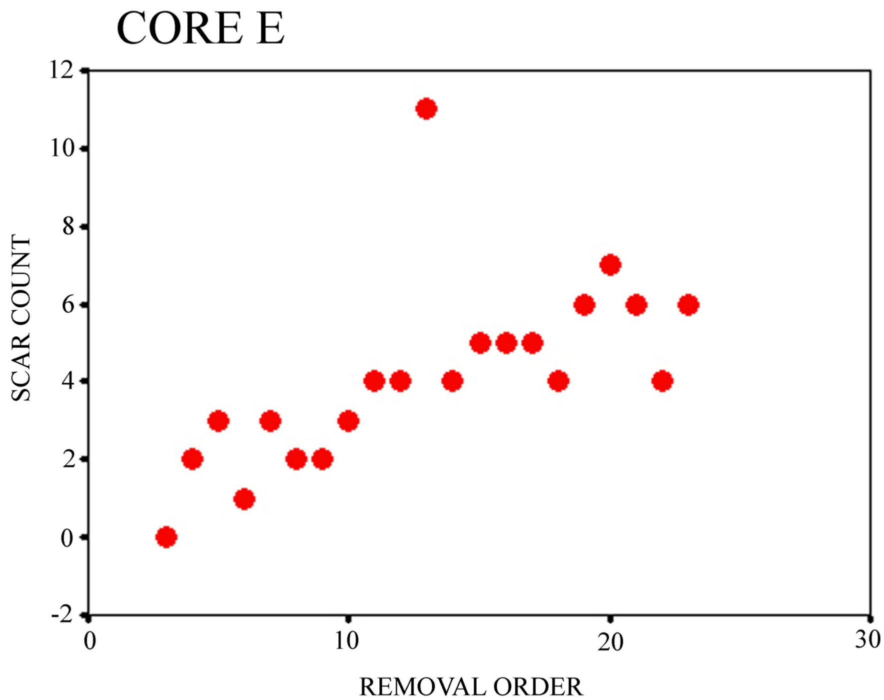

Figure 6. Scar count against removal order in Core E.

tinuous nature of some reduction 'sequences.' Yet as predictors of the precise order of removal of individual flakes from objective pieces, they can be 'wholly unsatisfactory' (Larson and Finley 2004: 102). The last conclusion follows from Larson and Finley's application of earlier continuous-reduction models to both a chosen subset of experimental flakes and to archaeological refit chains from the Hell Gap Paleoindian site in Wyoming, USA. In effect, regression models are best viewed as descriptions, not predictors. Considering the wide variation in salient properties, it is no surprise that models derived from a few biface reductions fail to predict the exact removal order of flakes from cores in other experimental or archaeological contexts. It would be surprising only if they did. As descriptions, models possess useful implications for our understanding of the nature of reduction, but they are not 'magic formulae' (Larson and Finley 2004: 102). Using them to predict removal order from other cores regardless of differences in all salient respects noted above is like using children's growth tables to estimate the weight of juvenile elephants at successive ages. Our intention here is to derive a formula for relative order of detachment first to characterize the 623x assemblage, and then to compare it to other assemblages' characteristic formulae.

ANALYSIS AND RESULTS

We started analysis with data screening. First we omitted all specimens identified as core-preparation flakes. Then we plotted analytical variables against removal order. Results were ambiguous in most cases, showing no clear relationship between flake attributes and removal order. At first glance, data from 623x resist treatment in continuous terms. Yet some refit chains patterned with removal order in some attributes. The clearest example is exterior-surface scar count in Core E ($r=.65$, $p<.01$; $r_s=.80$, $p<.01$) (Figure 6). At second glance, at least some attributes pattern continuously with reduction. Influenced—perhaps—by preconceptions about the nature of flint knapping in general, and by the certainty that the knappers were modern humans with cognitive abilities identical to our own, we have indeed formed the *a priori* opinion that the desired end products in this case were simply blades, and that no subsequent modification of those blades took place on site.

If individual attributes pattern somewhat ambiguously, then reduced dimensions of variation are worth examining. In metric data like ours, PCA often produces a first principal component (PC1) that can be interpreted as size, and a second component interpretable as one or more aspects of shape or technology. If flake size patterns inversely with reduction, then PC1 also should pattern inversely with flake removal order. PC2 also may pattern with removal order if flake shape or technology varies with reduction. Instead of seeking patterns in relatively many attributes, it may be more efficient to seek it in reduced dimensions, which are ratio-scale continuous variables. If there is a continuous dimension to core reduction, PCA might reveal it.

Accordingly, we conducted PCA on several sets of variables. In all cases, we included thickness, platform area, scar count, and exterior platform angle. We added length and width, flake area, or elongation separately, and analyzed all flakes except for platform-rejuvenation ones or only those whose elongation exceeded 2 (i.e., 'blades' by conventional terms) in several trial analyses on several cores. In testing these case and attribute combinations, we

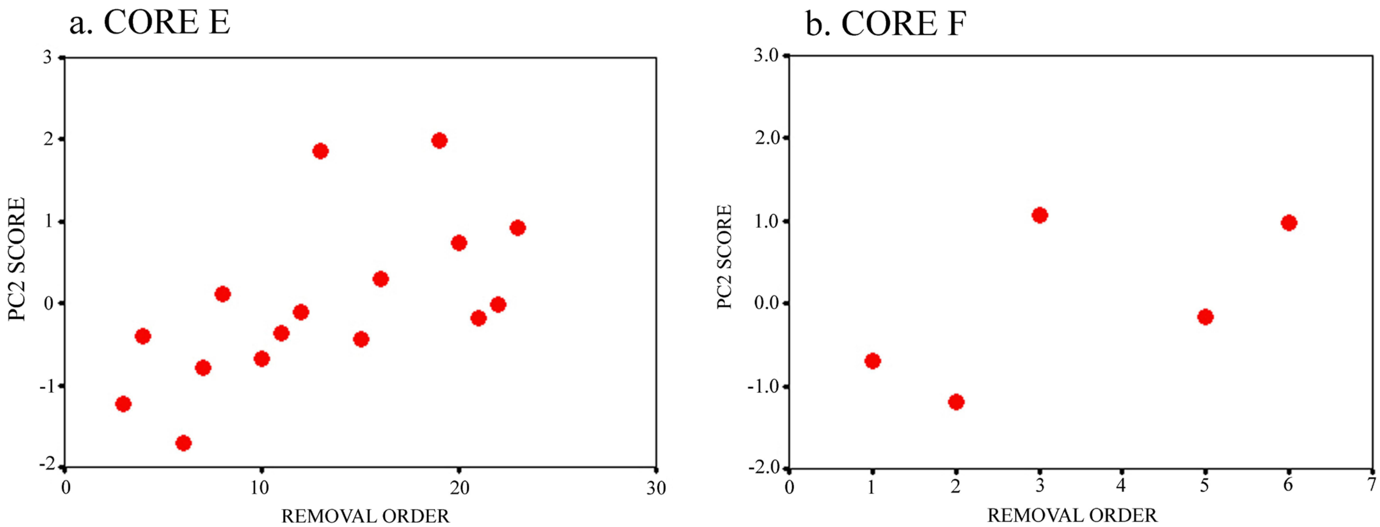

Figure 7. PC 2 against removal order: a) Core E, b) Core F.

found that two components always were extracted that together accounted for 70–85% of the original variance, and that flake-size attributes and scar count loaded highly and positively on PC1, exterior platform angle and sometimes platform area on PC2. Accordingly, we conducted PCA on all cores using the following attributes: thickness, flake area, platform area, scar count, and exterior platform angle.

As with simpler analysis, results generally were ambiguous. Only for Cores E and F did any component pattern with removal order, and it was PC2 in both cases. In both cases, PC1 is a size component and PC2 was determined by exterior surface scar count (i.e., scar count had a high positive load on PC2) and low platform-angle. These components emphasize technology, not shape. Where results were poor, PC1 also was an overall size component; PC2 generally indicated 'smallness' or 'lightness' (i.e., flake area and thickness loaded poorly on it), a low exterior surface scar count, and a high platform-angle dimension.

Figure 7 plots PC2 against removal order for these cores (for E, $r=.61$, $p<.02$ and $r_s=.70$, $p<.01$; for F, $r=.62$, $p=.26$ and $r_s=.60$, $p=.29$). Small sample size may partly explain the low p values for Core F. These plots show significant covariation, but are also more diffuse than the simple plot of Core E's scar count upon removal order. In Core F, scar count did not correlate significantly with removal order. Results do not appear to pattern by core type. Instead, they cross-cut core type (e.g., Cores D and E are opposed-platform blade cores while L and F are single-platform blade cores; D and L yielded no significant patterning while E and F did).

CONCLUSIONS

PCA reveals only limited continuous variation in refit chains from 623x, but it clearly shows that some exists. Given that practically all New World experimental work emphasizes bifacial reduction of flakes, the distinctive and particular technologies used to produce blades make comparisons difficult, raising the possibility that continuous models might be inappropriate or compromised. All refit chains were from varieties of blade cores. Although blades are defined traditionally as flakes at least twice as long as they are wide when measured at the longitudinal midpoint perpendicular to the axis of percussion (Bordes 1961; de Sonneville-Bordes and Perrot 1953), our results suggest that, for certain analytical purposes, it might be more useful to define them as lamellar flakes struck from prepared cores such that width only weakly influences length or shape. In blade cores, width has a rather narrow range of variation, while length is determined by core size, exterior-surface faceting and arrises (*arêtes*). As a result, each successive flake removal should be nearly the same length and width as the last and next. Continuous reduction models may be more suitable in bifacial reduction of cores and in biface production.

Data limitations are another factor that limits the utility of continuous models of reduction. Those models are documented best in experimental assemblages where all flakes were retained; essentially, they are complete, intact refit chains from first removal to last. As above, refit chains from 623x and most other archaeological examples are incomplete sequences.

FUTURE DIRECTIONS

Earlier work (Bradbury and Carr 1999; Ingbar et al. 1989; Shott 1996) and this analysis are small case studies in the modeling of reduction in continuous terms. Between them they document considerable promise but also mixed results. Not all kinds or circumstances of reduction are susceptible to modeling in continuous terms, at least on available evidence.

Of course, measurement and detailed analysis of more empirical refit chains will improve our understanding of these matters. But the most urgent need is for more systematic experimental data. We need many more replications that differ in all salient respects noted above and metric, not just typological, data from the resulting flake assemblages. Analyzing such data, archaeologists can determine when continuous approaches to reduction are legitimate and when they are not. In other words, we can establish or at least approximate the boundary conditions of continuous models. Boundary conditions are important epistemologically—for knowing *how* we know what we think we know about the human past. Many of anthropology's 'big questions' (e.g., origin of modern humans) are rather open-ended, heavily dependent on implicit preconceptions and assumptions and little constrained by the parameters of any recognizable conceptual framework. In contrast, the 'big questions' in physical science are classifiable by their boundary conditions. In the physical sciences, the boundary conditions establish what constitutes data, how hypotheses are formulated, how test implications are generated from them, and what criteria should be used to evaluate them. This paper is about a much smaller question—under what conditions might it be more useful to model flake removal as a fluid, flexible process, marked by continuous variation in metrical attributes, rather than a process marked by discrete stages (e.g., the *châine opératoire*). When variables are continuously distributed, regression or other approaches appropriate to interval or ratio-scaled data can express removal number as a function of various attributes, as shown in Table 3. If models are suitable and predictions are sufficiently precise, then removal number—not just order—can be estimated from models and attribute values. Gaps in removal number estimates in archaeological refit chains are a monitor of flakes retained for use and carried off-site. In this way, archaeologists can estimate the number of flakes removed from refit chains and their relative and absolute order.

To judge from the literature, many Stone Age archaeologists in both hemispheres are committed to stage-based lithic reduction models like those of Callahan (1979) and Böeda (1993). Despite a certain logical coherency, some doubt that continuous methods are useful in the study of reduction sequences. Perhaps advocates like us are too uncritical in using the approach and urging it upon others. At this point, however, none of us really knows whose perspective is the better supported empirically (if indeed a single view can, or should, be considered valid), nor under what conditions discrete or continuous models might best be applied. Only systematic replication data and their thorough analysis can settle the matter. Until then, data from 623x and other refit chains only partly support continuous models. However, lithic reduction is clearly multidimensional and affected by a host of contingent circumstances, rather than rigidly deterministic (Clark 2002). Our study shows that one dimension of flake variation in reduction is continuous. There may be others, but we will not find them if we do not look for them.

ENDNOTE

[1] Callahan revised his views several times over the past 30 years. Depending on the edition (cf., e.g., 1979, 1996), he lists either five or six basic stages, in ascending order from blank to finished tool. In the original 1979 work, the stages were: (1) blank (i.e., unmodified flake), (2) rough out, (3) primary preform, (4) secondary preform, (5) final perform, and (6) finished tool. Later, Callahan added a seventh stage for 'retouched implement,' by which he meant a finished tool that was resharpened after manufacture to prolong its use life. The remaining three stages were interposed between (5) and (7) and referred specifically to fluted bifacial points. A final stage (9) was the equivalent of stage (7) above. The stages were defined experimentally and consisted of a mix of 20 (sometimes ambiguous) technological (e.g., width/thickness ratio), morphological (e.g., regularity in plan view) and behavioral (e.g., degree of concentration required during manufacture) characteristics (Callahan 1979: 30, 31). Although there is vectored change in a number of variables (e.g., metric dimensions decline and the number of facets increases throughout the sequence), some of the 'stages' are themselves questionable (e.g., when fluting occurs is not necessarily a valid stage marker). Although he used 'stage' repeatedly, he also acknowledged that the stages somewhat arbitrarily subdivide a continuum of joint metric/technological variation. So stage assignment is rather like deciding where the boundary lies between red and orange in the visible-light spectrum.

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