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Constraints on Levallois Core Technology: A Mathematical Model

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Recent volumetric definitions of Levallois core technology are amenable to mathematical modelling. We present a simple geometric model that permits controlled manipulation of a few of the key parameters defining Levallois core morphology. The models indicate that Levallois cores are relatively efficient at minimizing raw material waste while at the same time maximizing productivity in terms of total number of tool blanks and amount of cutting edge produced. Deviations from an ideal Levallois geometry produce significant declines in both efficiency and productivity. These results implicate mechanical and economic constraints as factors underlying the broad geographic distribution and temporal persistence of Levallois core technologies during the Middle and Late Pleistocene. © 2001 Academic Press

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Introduction

The ubiquity of Middle Paleolithic prepared core reduction strategies, commonly referred to as Levallois or Mode III technology, across much of Eurasia and Africa during the Middle and Late Pleistocene is surprising from both ecological and evolutionary standpoints. As a general rule, populations or communities of organisms with wider geographic distributions or longer temporal ranges tend to exhibit great behavioural and biological diversity (Brown & Lomolino, 1998: 372–376; MacArthur & Wilson, 1967; Rosenzweig, 1995). With geographic isolation, continuous adaptation to changing local conditions and drift tend to enhance differences among populations and communities. The wide distribution of hominid populations during the Middle and Late Pleistocene should have led to increasingly divergent lithic technological systems driven by differences in raw material abundance and quality and the demands placed on lithic technologies in variable environmental contexts. Yet Levallois core technology is essentially similar in its fundamental geometric organization from southern Africa through Siberia and Mongolia (Figure 1) (Boëda & Muhesen, 1993; Brantingham, 1999; Derevianko, Shimkin & Powers, 1998; Derevianko & Petrin, 1995*a*; Jaubert *et al.*, 1997; Rolland, 1995; Van Peer, 1992, 1998), and from the early Middle Paleolithic to the Initial Upper Paleolithic (Kuhn, Stiner & Gülec, 1999; Marks, 1990; Ohnuma & Bergman, 1990; Svoboda & Svoboda, 1985; Svoboda, Lozek & Vlcek, 1996). The apparent stability of the basic model of Levallois core technology in these diverse contexts demands explanation.

It is the contention of this paper that the ubiquity and apparent stability of Levallois core technology is due in large part to economic and mechanical constraints on chipped stone technologies. This position contrasts with that recently advanced by Foley & Lahr (1997) suggesting that the development and conservative appearance of Levallois-Mode III core technologies is linked to the evolution and dispersal of a particular hominid species, most likely *Homo heidelbergensis* and its phylogenetic descendents. They conclude that Levallois core technology serves as a reliable phylogenetic marker for this taxon. While the actual mechanisms linking the two are not formally spelled out, their conclusions appear to be based on an assumed species-specific ecological niche and/or strictly bounded cognitive ability (see also Carbonell *et al.*, 1999; Larick & Ciochon, 1996).

We maintain that hominid phylogeny is a relatively unimportant constraint on the character and persistence of lithic technologies, being overridden in most contexts by mechanical constraints and economic and ecological processes. We explore this perspective using a mathematical model of core reduction based on simple geometric principles. Using only a minimal set of mathematical rules, the model provides a means for assessing the "sensitivity" of several technological parameters governing core reduction and places boundaries on the gross efficiency and productivity

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Figure 1. Map showing the geographic distribution of Levallois-like core technologies between approximately 250 and 30 ka. Based on Foley and Lahr (1997: 13–16). Regions: (1) arid Africa; (2) West Asia; (3) West and Central Europe; (4) South Asia; (5) Siberia; (6) Mongolia and arid Central Asia.

of Levallois cores. The model suggests that Levallois core technology as currently defined is efficient in minimizing preparation waste and productive in maximizing the number of usable end products and amount of usable cutting edge. However, deviation from the basic Levallois geometry results in significant declines in both raw material efficiency and productivity. Levallois core technology appears to be one optimal solution to some of the potential costs associated with core reduction. The efficiency and productivity exhibited by Levallois core technology, combined with the mechanical constraints inherent in lithic reduction, are sufficient grounds to hypothesize the repeated, independent convergence on the basic Levallois core geometry in diverse contexts.

Levallois Core Technology

Levallois technology frequently is defined as a method for producing flake blanks with standardized dimensions and certain surface attributes. The classic position, developed by Bordes (1961: 14), and still widely employed, defines Levallois as "un éclat à forme prédéterminée par une préparation spéciale du nucléus avant enlèvement de cet éclat." The size, shape and character of Levallois blanks are thought to be predetermined by shaping stone cores in such a way as to allow the knapper to control how applied force will propagate through the raw material and detach a desired flake. Commonly, Levallois cores used for producing predetermined blanks are flat-faced, display unidirectional, bidirectional or centripetal surface preparation, and have faceted striking platforms with platform angles approaching 90°.

While a shape control system undoubtedly exists for certain Levallois core forms (see Van Peer, 1992), there remain a number of significant problems with defining Levallois technology solely on the basis of the production of predetermined blanks (Chazan, 1997; Dibble, 1989). Not only is there considerable disagreement over what set of standard attributes and dimensions should be used to characterize a typical Levallois product, but also it has been demonstrated that very different core forms can produce seemingly diagnostic Levallois pieces (e.g., Dibble, 1989; Marks & Volkman, 1983).

The recognition of such problems has led to a redefinition of Levallois technology that focuses primarily on the geometric construction of cores (Figure 2) (Boëda, 1990, 1995). This definition shifts attention away from the production of pre-determined blanks, though it does not exclude this as one objective of Levallois technology. The fundamental notion is that core reduction is based on a three-dimensional spatial model of the mass of raw material to be worked. Five technological criteria characterize this definition of Levallois (Boëda, 1990, 1995; Chazan,

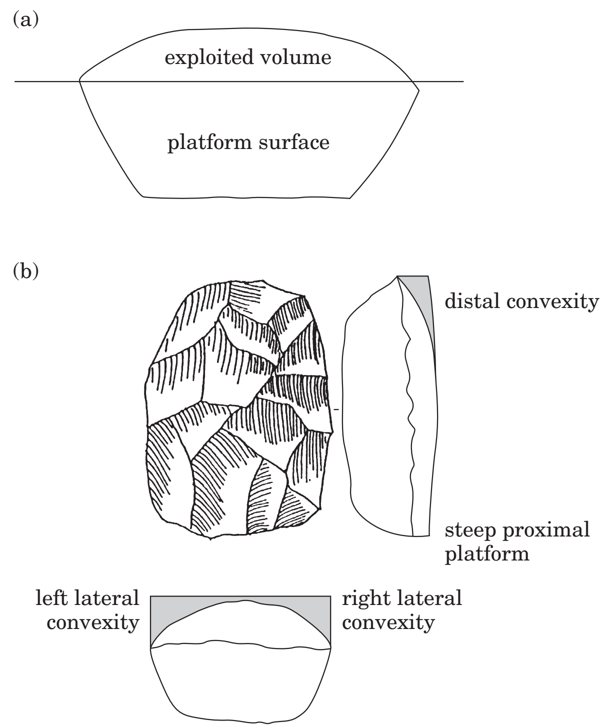

Figure 2. (a) General illustration of the two hierarchically related surfaces that define a Levallois core. (b) The production of flakes of pre-determined size and shape is dependent on maintaining the distal and lateral convexity of the core, the position of negative removals and the angle and thickness of the platform. All are critical for channeling the force of a percussion blow in desired directions. Modified after Boëda (1995).

1997: 724): (1) exploitation of the volume of raw material is organized in terms of two intersecting planes, or flaking surfaces; (2) the two surfaces are hierarchically related, one constituting the striking platform and the other the primary reduction surface; (3) the primary reduction surface is shaped such that the morphology of the product is pre-determined, which is fundamentally a function of the lateral and distal convexities of the surface; (4) the fracture plane for removing primary products is sub-parallel to the plane of intersection of the two surfaces; and (5) the striking platform size and shape is adjusted to allow removal of flakes parallel to this plane, usually through retouch or faceting.

This volumetric definition of Levallois core technology encompasses a substantial range of archaeological variability. The definition states only that a primary reduction surface is organized in terms of lateral and distal convexities to facilitate the production of blanks of pre-determined morphology. It does not restrict how this shape is achieved. Thus, pieces of raw material that begin with appropriate natural convexities and require little additional preparation could fall within the volumetric Levallois definition alongside heavily prepared centripetal cores that meet the strict typological definition (Brantingham *et al.*, 2000; Kuhn, 1995*b*; see also papers in Dibble & Bar-Yosef, 1995). Similarly, the volumetric definition does not specify what technological actions (if any) are necessary to establish a hierarchical relationship between the primary reduction surface and the striking platform, nor how the platform is prepared to ensure the production of pre-determined blanks. There are presumably a number of different methods and sequences of technological actions by which these fundamental volumetric relationships can be achieved. The only additional component of the volumetric definition is the utilization of hard hammer percussion, probably a necessity when attempting to work steep platform angles.

In total, a wide range of core morphologies may be classified as Levallois technology. The variability between such forms is a result of the diverse techniques used in implementing the Levallois method, rather than the use of radically different reduction strategies. Baumler (1988, 1995), among others (Marks & Volkman, 1983), emphasizes that any core technology is by necessity dynamic, since it must manage an ever-decreasing amount of raw material as well as the irreversible consequences (positive or negative) of each subsequent removal from the core. A certain degree of variability in Levallois core technology is explained by these dynamic adjustments made during core reduction. The variable occurrence of, for example, cortex trimming, platform faceting, edge preparation and a host of other technical attributes may reflect such adjustments over the life of a core. Other features of Levallois variability including differences in the character of surface preparation and orientation of removals (e.g., unilinear parallel, unilinear convergent, centripetal) may persist despite differences in raw material, or errors encountered during reduction. However important, such variability does not alter the fundamental volumetric model of Levallois core reduction.

Mathematical Models of Core Reduction

Volumetric models of core reduction like that used to describe Levallois technology may be translated into mathematical form with relative ease. Basic geometric principles may be used to describe how technological actions such as the preparation of a steep striking platform effect the overall volume of raw material available for use and its conversion into usable blanks.

For the purposes of simplification, all of the following models are two dimensional. The models describe the reduction of ovoid, well rounded alluvial cobbles. They assume that core reduction involves a few essential steps such as the positioning and preparation of at least one striking platform, and the establishment of a primary reduction surface. Figure 3(a)–(e) shows a hypothetical river cobble in longitudinal view. In this case, the cobble has been worked into a single platform core with a moderately steep platform positioned near the end of the long axis. The primary reduction surface

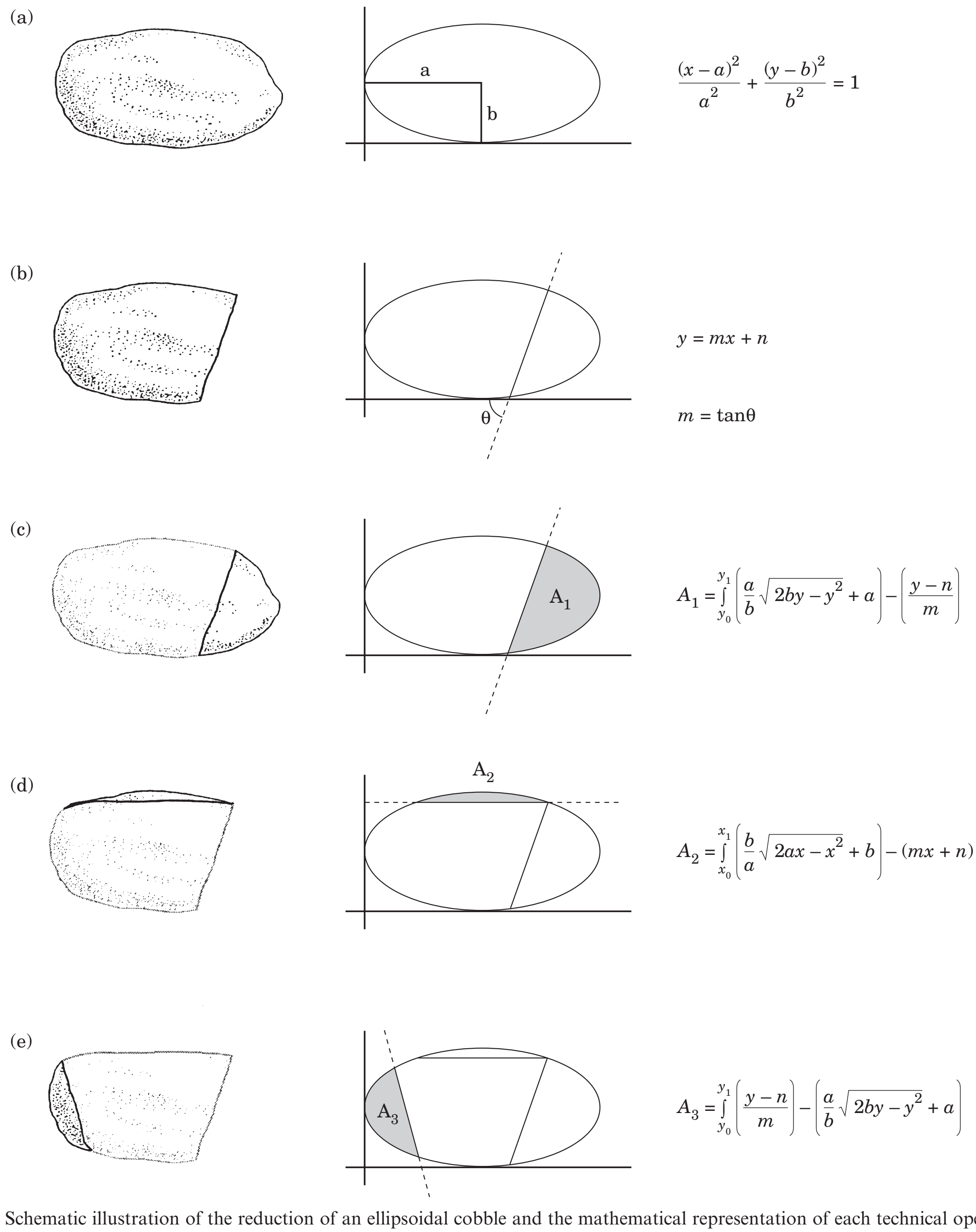

Figure 3. Schematic illustration of the reduction of an ellipsoidal cobble and the mathematical representation of each technical operation. (a) the initial cobble is modelled as an ellipse; (b) the platform position and angle is modelled as a line crossing the ellipse with two points of intersection; (c) the area of platform preparation waste (A_1) is calculated by integrating the difference between the line and the ellipse; (d, e) similar procedures are used to calculate the area associated with the primary reduction surface (A_2), or a secondary striking platform (A_3). See text for additional description of mathematical operations.

is a plane oriented parallel to the long axis and meets the platform at the edge of the cobble.

This hypothetical core may be represented mathematically by considering four independent variables including the shape and size of the original nodule, platform position and platform angle. Here nodule shape and size are modelled as an ellipse given by:

$$\frac{(x-a)^2}{a^2}+\frac{(y-b)^2}{b^2}=1 \tag{1}$$

where x and y are points along the ellipse, and a and b are the x-intercept and y-intercept, respectively (Anton, 1988: 718) (Figure 3(a)). Expressed in terms of y this gives:

$$y=\frac{b}{a}\sqrt{2ax-x^2}+b \tag{2}$$

Thus, for any known value of x it is possible to calculate the corresponding value of y which falls along the ellipse. Note that cobbles of variable initial shapes and sizes are determined by choosing different arbitrary values of a and b. For example, low values of b relative to a produce flattened ellipses, whereas values of b approaching a produce more circular ellipses.

The position of the striking platform is described by a line crossing the ellipse and intersecting it at two points (Figure 3(b)). The line representing the platform is described by the standard equation:

$$y=mx+n \tag{3}$$

where x and y are points along the line, m is the slope of the line and n is the y-intercept. The relationship between the slope of the line (m) and the platform angle (θ) is described by the equation $m=tan\theta$ (Anton, 1988: 39) (Figure 3(b)).

The upper point of intersection between the line and the ellipse defines the position of the initial striking platform. This upper point, here designated (x_1, y_1), may be arbitrarily chosen from all of the possible points that fall along the ellipse. The lower point of intersection between the line and the ellipse, here designated (x_0, y_0), can be determined by substituting (2) in the standard equation for a secant line (Anton, 1988: 139):

$$m=\frac{y_1-\left(\frac{a}{b}\sqrt{2ax_0-x_0^2}+b\right)}{x_1-x_0} \tag{4}$$

Given known values of x_1 and y_1 and an arbitrary platform slope (m) it is possible to calculate the corresponding lower point (x_0, y_0) where the line and the ellipse intersect.

Notice that the area between the platform line and the ellipse represents the amount of material removed in preparing the platform. This "preparation waste" can be determined by integrating (in terms of y) the difference between the two curves (Anton, 1988: 368–372) (Figure 3(c)):

$$A_1=\int_{y_0}^{y_1}\frac{a}{b}\sqrt{2by-y^2}+a-\frac{y}{m}+\frac{n}{m} \tag{5}$$

which gives:

$$A_1=\left[\frac{a}{b}\left(\frac{y-b}{2}\sqrt{2by-y^2}+\frac{b^2}{2}\cos^{-1}\left(1-\frac{y}{b}\right)\right)+ay-\frac{y^2}{2m}+\frac{ny}{m}\right]_{y_0}^{y_1} \tag{6}$$

In sum, a straightforward set of mathematical procedures may be used to model the position, angle and amount of raw material waste resulting from the preparation of a striking platform at one end of an ellipsoid cobble. The same procedures may be repeated for determining the location and amount of preparation waste associated with the preparation of a primary reduction surface or a second platform (Figure 3(d)–(e)).

Flexibility of the Models

The mathematical variables discussed above may be used to represent a wide range of core technologies. It is well known that the shape and size of the initial raw material blank places constraints final core form (Kuhn, 1995*b*; Toth, 1982). Following a path of least resistance, for example, working an elongate, pointed cobble is much more likely to result in the production of a proto-biface than a spheroid (Toth, 1982; Schick & Toth, 1993). The present model manages such variability with straightforward adjustments to the dimensions of the ellipse. Ellipses may be slightly less realistic for modelling the reduction of angular nodules. Yet, it is possible to draw some general conclusions from the geometry of ellipses to more irregular shapes.

Other technological variables—those more directly determined by the reduction strategy—are well resolved in the following mathematical models. Fundamental variability in core morphology is determined by platform position and platform angle (Figure 4(a)–(d)). Any change in the position of the platform causes a change in the position of the primary flaking surface since, by definition, the primary platform and primary reduction surface meet at a point along the edge of the ellipse. For example, placing the striking platform at a position close to the end of the long axis of the cobble results in a thin core (Figure 4(a)), whereas shifting the platform towards the centre of the core along the circumference of the ellipse results in a thick core (Figure 4(b)).

Changes in platform angle have a similarly profound impact on core morphology. Holding platform position constant, changes in platform angle produce "steep angle" cores (i.e., platform angles approaching 90°), "acute angle" cores (i.e., platform angles less than 45°) and all manner in between (Figure 4(c)–(d)).

Cores with steep platform angles closely resemble Levallois core reduction strategies (Boëda, 1991, 1995; Van Peer, 1992). Indeed, the steep angle cores modelled here satisfy four of the five volumetric criteria used to characterize Levallois core technology (see Chazan, 1997). Criteria 1 and 2, namely the organization of the core as two hierarchically related flaking surfaces that meet at a single plane of intersection, are accurately modelled by two lines crossing an ellipse and sharing a single point of intersection. Criterion 4,

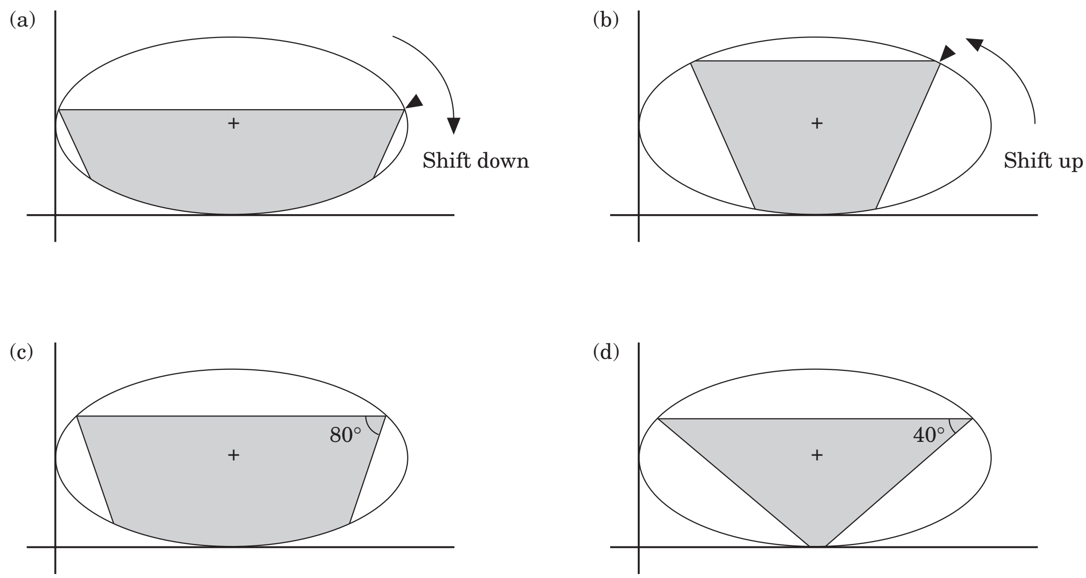

Figure 4. Mathematical representation of variable core morphologies. (a, b) illustrate how shifting the platform up or down along the circumference of the core creates cores of different primary dimensions. (c, d) illustrate how simple changes in platform angle radically alter the overall organization of the core.

which requires a sub-parallel plane of flake removal, is accurately modelled by orienting the line representing the primary reduction surface parallel to the long axis of the ellipse. Criterion 5, or the preparation of a striking platform with an appropriate angle and thickness relative to determine endproduct characteristics, is easily modelled by changes in the slope of the line representing the platform (see Chazan, 1997: 722). The present models do not satisfy Criterion 3, namely the use of lateral and distal convexities on the primary flaking surface to control the morphology of endproducts. Clearly this aspect of the definition of Levallois technology is of greater relevance to the morphology of endproducts than to the basic volumetric structure of the core. Nevertheless, the models could be modified to address this criterion in the future by substituting various parabolic lines for the straight lines used here.

Cores with relatively acute edge angles are technologically quite different from the steep angle cores, which closely resemble Levallois (Figure 4(d)). Most importantly, increasingly acute flaking angles erases the hierarchical relationship between flaking platform and primary flaking surface (Levallois Criteria 1 and 2). An acute platform angle may also modify the plane of flake removal (Levallois Criterion 4), and certainly alters the relationship between platform thickness, platform angle and final blank morphology (Levallois Criterion 5). Thus acute angle cores differ in several fundamental aspects from Levallois technology, resembling in many respects half of a bifacial core.

It is important to emphasize that these mathematical models do not attempt to completely "replicate" Levallois, or any other core reduction strategy. They do, however, allow exploration of essential economic and technical features of different core forms.

Core Technologies and Raw Material Economy

The economic value of a core technology may be measured in many currencies. Three common currencies are discussed here: (1) the amount of lithic raw material waste generated in core preparation; (2) the number of endproducts produced by cores of various morphologies; and (3) the cumulative length of cutting edge produced by these cores. The goals are to identify optimal core morphologies for minimizing preparation waste, maximizing number of endproducts and maximizing the total amount of usable cutting edge, and to learn whether these optima coincide or are mutually exclusive.

The mathematical basis for calculating the amount of waste generated in core preparation was discussed previously (see Figures 3(a)–(e)). Total waste is the sum of the amount of waste produced in preparing one or more striking platforms and the primary reduction surface (Figure 5(a)). Only single platform cores are discussed here to simplify the interpretation of results. The amount of preparation waste generated by different modelled cores is expressed as a percentage of the total area of the initial idealized cobble. Waste generated by maintenance of the primary surface and striking platform is not considered, but is expected to be minimal compared to waste from initial preparation.

The number of endproducts and cumulative length of cutting edge are determined by first assuming a

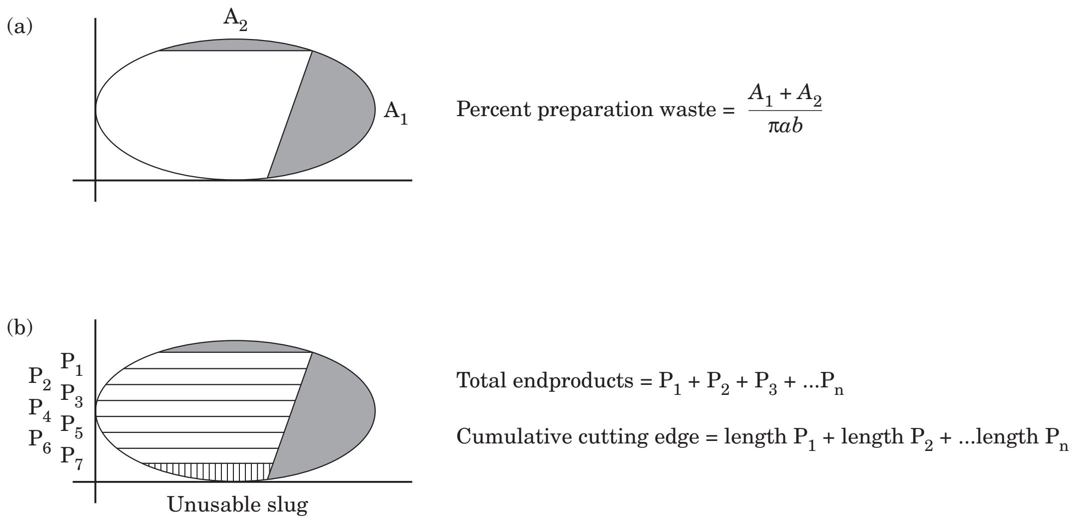

Figure 5. Mathematical representation of the economic currencies commonly associated with core technologies. (a) method for calculating the percent preparation waste for single platform cores. (b) method for calculating the total number of end products and cumulative cutting edge generated by a core. Note the unusable slug, which is a constant thickness in all models.

standard thickness for all endproducts. The total number of endproducts is the total thickness of the prepared core divided by the standard endproduct thickness (Figure 5(b)). For example, a prepared core that is 10 cm thick can theoretically produce a maximum of five endproducts that are 2 cm thick. Note that this aspect of the model approximates recurrent Levallois core reduction, rather than lineal methods (see Boëda, 1990, 1995; Chazan, 1997). Realistically, core reduction stops with an unusable "slug" of raw material that is too small to be effectively manipulated. This "slug" reduces the number of endproducts by a fixed amount regardless of the initial shape or size of the blank, or morphology of the core. A standard slug thickness of two arbitrary units is used in all of the following models.

The cumulative length of cutting edge produced is theoretically the sum of the lengths of all the endproducts generated multiplied by some factor (Figure 5(b)). The actual length of cutting edge is dependent on the shape of the endproducts. Standardized, symmetrical endproducts (e.g., blades) have a predictable relationship between length and cutting edge. For example, the amount of cutting edge for a large blade is roughly two times its length. Asymmetrical or irregular blanks exhibit complex relationships between flake length and amount of cutting edge. For the sake of simplicity, the following analyses present only cumulative length of endproducts, and assume that this reflects cumulative length of cutting edge in some predictable manner.

Results

Within the parameters of the model, variability in core morphology is dictated by changes in platform position and platform angle. The principal economic currencies presented above may be measured against platform position and platform angle to explore the efficiency and productivity of various hypothetical core forms. The models are based on two ellipses; one that is 40 arbitrary units long and 20 units thick, with an initial area of 628·32 square units; and another that has the same initial area, but is 80 units long and 10 units thick. The first hypothetical cobble is more circular, while the second is flatter. Core width is not addressed directly in these models, but may be assumed to be constant in all cases.

Platform position is reported as a percentage of total core length. It should be remembered, however, that for the various modelled cores platform positions shift in two dimensions along the curvature of the ellipse. Thus, for the first hypothetical cobble, a platform positioned at 50% of the initial cobble length has a coordinate position $x_1=20$ and $y_1=20$ (Figure 6(a)). At 100% of the initial cobble length the platform has a coordinate position of $x_1=40$ and $y_1=10$ (Figure 6(b)). A platform positioned at 80% of the initial cobble length has a coordinate position of $x_1=32$ and $y_1=18$ (Figure 6(c)). Platform positions for the second hypothetical cobble are also reported relative to total cobble length. Because the dimensions of this second ellipse are different from those of the first, however, the absolute distances are different. Thus, a platform located at 50% of initial cobble length has a coordinate position of $x_1=40$ and $y_1=5$. Direct comparisons between the cobbles are facilitated by treating these absolute distances as percentages of the total cobble lengths.

As discussed above, steep angle cores with platform angles of 80° are taken as representative of Levallois technology. Acute angle cores with platform angles of

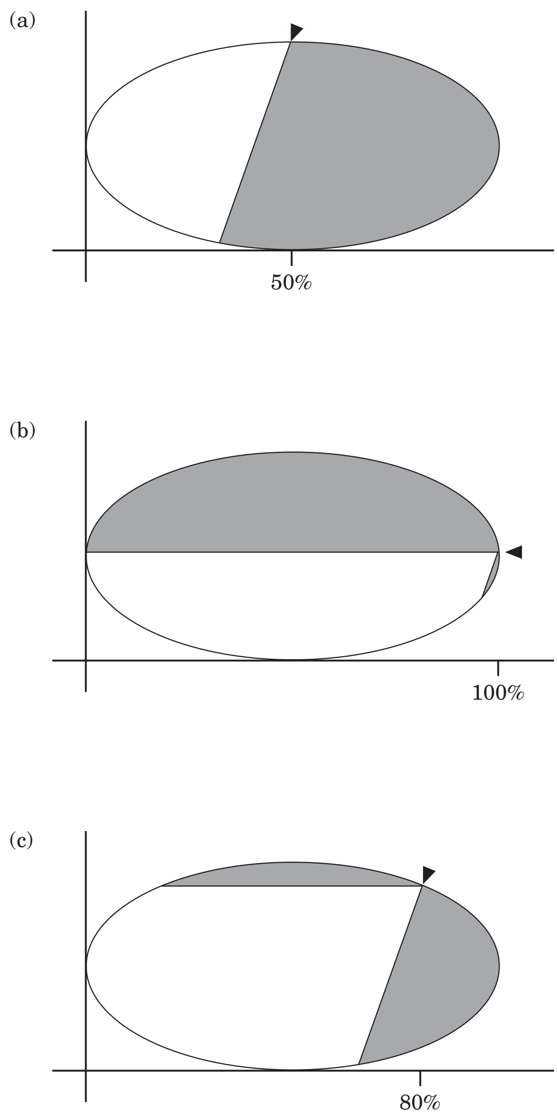

Figure 6. Platform positions for modelled cores shift along the curvature of the ellipse in two dimensions, but are reported as a percentages of initial cobble lengths to facilitate comparisons between cobbles of different shapes. (a) steep angle core with the platform positioned at 50% of initial cobble length. (b) steep angle core with the platform positioned at 100% of initial cobble length. (c) steep angle core with platform positioned at 80% of initial cobble length. Shaded areas represent waste removed in preparation of the cores.

40° simply represent one example of divergence from the basic Levallois geometry.

Figure 7 graphs percent preparation waste against percent platform position for both steep and acute angle cores based on the first hypothetical cobble (40 × 20 units). The graph tracks how percent preparation waste changes as platform positions migrate from the centre to the edge of the core and cores become flatter (see Figure 4(a)–(b)). For steep angle cores, percentage preparation waste reaches a maximum (56·0% of area) when the striking platform is positioned near the centre of the original cobble, and reaches similarly high values (50·0%) at the extreme edge. Preparation waste is minimized (21·1% of area) when the platform is positioned at 87·5% of the total length of the core. For acute angle cores the pattern somewhat different. In this case, preparation waste reaches a maximum (87·3% of area) also at the centre of the original cobble, but is at a minimum (39·9%) at 92·5% of the total cobble length.

Comparisons between the two hypothetical core types reveal very significant differences. Steep platform angles consistently generate less preparation waste compared with acute angles, regardless of platform position. When steep angle cores are at their most efficient point and acute angle cores their least, there is a maximum difference of 66·2% preparation waste. When both core forms are at their most efficient platform positions steep platform cores still outperform acute angle cores by 18·8%. Thus, it is possible to conclude that steep platform cores are minimally about 20% more efficient than acute platform cores in converting raw material to usable blanks.

Most importantly, Figure 7 suggests that steep angle cores are more flexible in minimizing preparation waste, or more forgiving of errors in setting up the platform. The more shallow, basin-like curve shown for steep angle cores suggests that even major shifts in platform position have relatively minor influence on total waste generated. For example, shifting the platform anywhere between about 82% and 90% of initial cobble length will maximally increase preparation waste by 2%, and between 77% and 92% of initial cobble length preparation waste increases at most by only 5%. Acute angle cores exhibit much less flexibility. Achieving minimum waste levels requires very precise positioning of the striking platform at approximately 92·5% of initial cobble length. Allowing for a 5% increase in preparation waste means that the platform can be positioned between about 87% and 97% of cobble length.

The importance of initial cobble shape is expressed in patterns of percent waste generated by acute angle cores made on flatter cobbles (Figure 8). Switching production of acute angle cores to flatter cobbles produces gains not only in overall raw material efficiency, but also the relative flexibility of platform positioning. Minimum preparation waste for acute angle cores decreases from 39·9% to 23·3% of area when based on flatter cobbles (compare Figures 7 and 8). This gain brings acute angle cores close to the maximum efficiency of steep angle cores. Increased flexibility in platform positioning also accompanies the switch to flatter cobbles, as is clear in the more basin-like profile for acute angle cores shown in Figure 8. Not surprisingly, acute angle cores are most efficient in minimizing preparation waste when based on cobbles that initially resemble the intended core form.

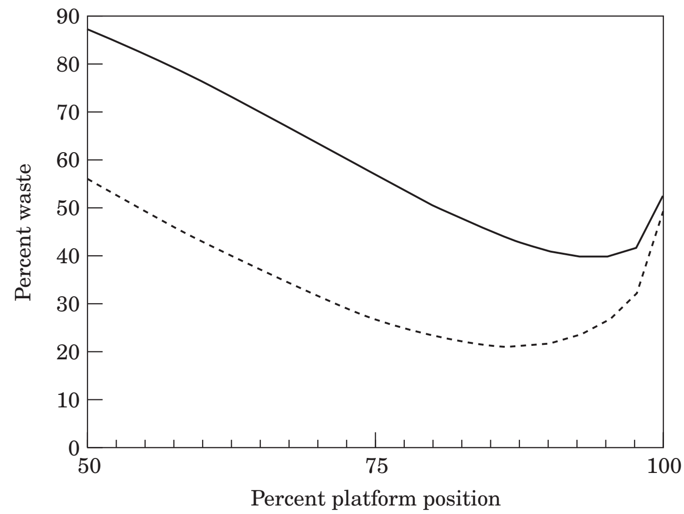

Figure 7. Percent preparation waste is graphed against platform position as a percent of initial cobble length for steep and acute angle cores based on the same initial cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

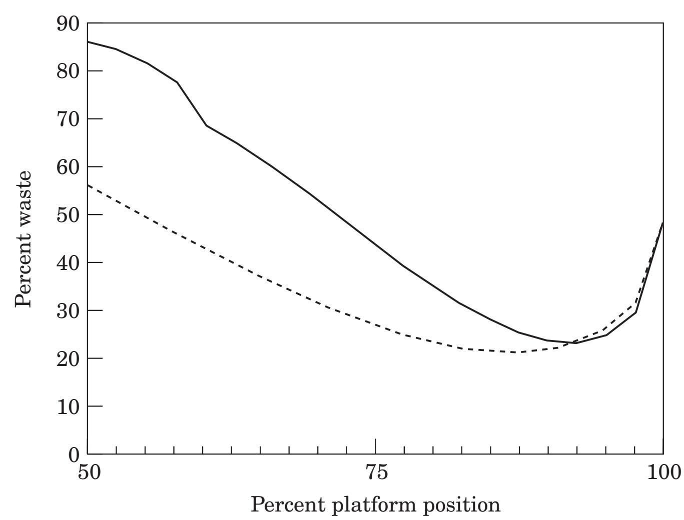

Figure 8. Percent preparation waste is graphed against platform position as a percentage of initial cobble length for steep and acute angle cores. The acute angle core is based on a flatter initial cobble (80 × 10 units). The steep angle core is based on the more circular cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

The productivities of acute and steep angle cores also vary significantly. Steep angle cores consistently yield equal or greater numbers of endproducts over the entire range of platform positions (Figure 9). However, the absolute differences in productivity are not great. Steep angle cores appear to be most productive when the platform is positioned closer to the centre of the original cobble, which would suggest that initial core thickness is the most important variable governing core productivity. In contrast, acute angle cores show fairly even productivity over most platform positions, with productivity declining rapidly only when platforms are positioned very close to the edge of the cobble. Most platform positions (between 50% and 92·5% of cobble length) yield either 9 or 10 blanks. The general implication is that steep angle cores can be more productive than acute angle cores, though acute angle cores have a more "stable" yield of blanks across all platform positions. Consistent blank yield is apparently not dependent upon initial cobble thickness for acute angle cores.

The gains in raw material efficiency seen by shifting acute angle core reduction to flat nodules are not matched in core productivity. Rather, core productivity radically decreases (Figure 10). There is an apparent tradeoff that comes with the reduction of acute angle cores: Maximize raw material efficiency by selecting flat cobble blanks, or maximize productivity by selecting cobbles with more circular cross-sections. This tradeoff is not as apparent with steep angle cores,

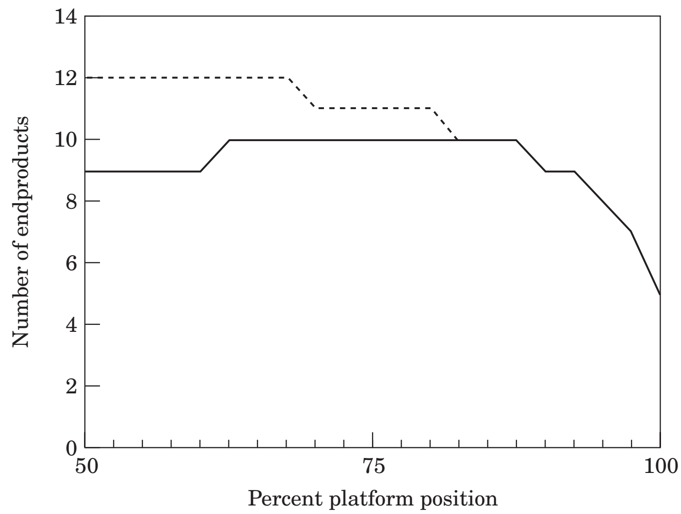

Figure 9. Number of end products is graphed against platform position as a percentage of initial cobble length for steep and acute angle cores based on the same initial cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

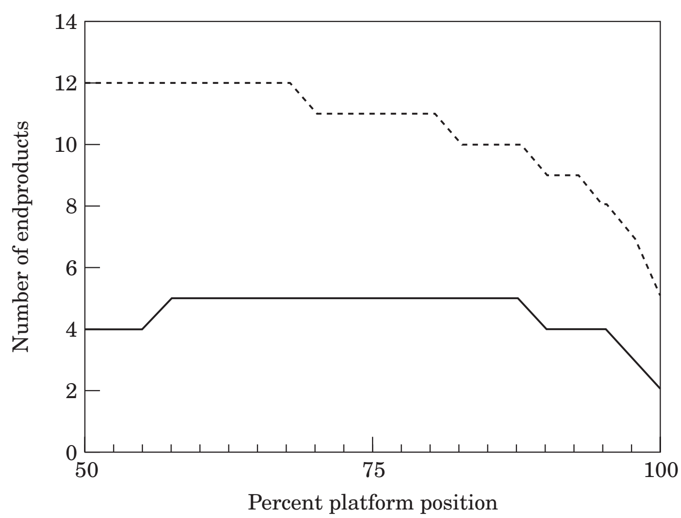

Figure 10. Number of end products is graphed against platform position as a percent of initial cobble length for steep and acute angle cores. The acute angle core is based on a more elongate initial cobble (80 × 10 units). The steep angle core is based on the more circular cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

where high productivity generally coincides with high raw material efficiency. A tradeoff of this nature may be especially important where waste flakes have no independent utility (e.g., as casual tools), where raw material is scarce, or if extensive core preparation increases the likelihood of core failure (Brantingham *et al.*, 2000). Under these circumstances extensive waste is likely to be a distinct disadvantage to tool makers, even where production is focused on standardized blanks.

These above contrasts between steep and acute angle cores are also reflected in the cumulative amount of cutting edge produced. Figure 11 illustrates that steep angle cores yield significantly more usable cutting edge over the entire range of platform positions when both core types are based on more circular cobbles. Peaks in cutting edge productivity generally coincide with high raw material efficiency for both steep and acute angle cores. However, any attempt to improve raw material efficiency in acute angle cores by switching to flatter cobbles results in massive decreases in cutting edge productivity (Figure 12).

Discussion

A number of significant conclusions can be drawn from the basic models presented above. Most importantly, it would appear that steep angle cores, which are here taken as representative of Levallois technology

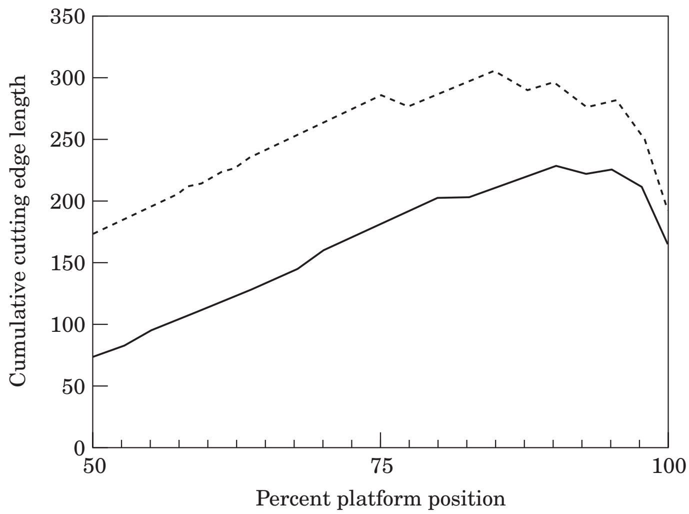

Figure 11. Cumulative cutting edge length is graphed against platform position as a percent of initial cobble length for steep and acute angle cores based on the same initial cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

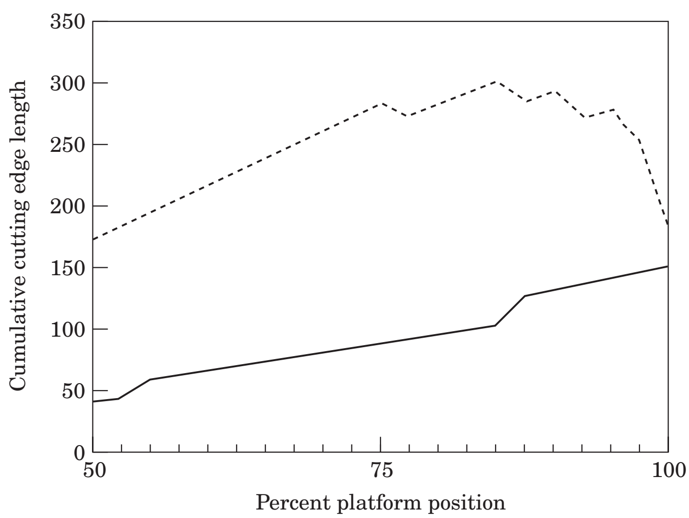

Figure 12. Cumulative cutting edge length is graphed against platform position as a percentage of initial cobble length for steep and acute angle cores. The acute angle core is based on a flatter initial cobble (80 × 10 units). The steep angle core is based on the more circular cobble (40 × 20 units). ——, acute angle; – – –, steep angle.

in its broadest sense, are overall more efficient, more flexible in platform positioning and more productive than cores with more acute platform angles. Maximum raw material efficiency in this model Levallois technology is achieved when the platform is located at a position approximately 87·5% of the total length of the initial cobble. Preparation waste increases little if the platform is situated anywhere between about 77% and 93% of the total length of the cobble.

Maximum efficiency for acute angle cores also is achieved with platform positions close to the extreme proximal end of the initial cobble, but there is less leeway for changing platform position without producing significant increases in preparation waste. Acute angle cores can approach the raw material efficiency of steep angle cores, but only given very precise core preparation. This situation can be further improved by switching production to flatter cobbles. Starting with similar initial cobbles, however, acute angle cores cannot surpass the efficiency of steep angle cores, which are between 65% and 20% more efficient in minimizing stone raw material waste, depending on platform position.

In terms of productivity, steep angle Levallois-like cores produce as many, and often greater numbers of usable tool blanks per unit volume compared with acute angle cores, and cumulative cutting edge productivity is always greater. Whereas shifting to flatter cobble blanks does improve the raw material efficiency of acute angle cores, it also results in serious drops in flake blank productivity.

The primary limitation of these models stems ironically from their mathematical regularity. In practice, knappers must respond to the often unpredictable nature of stone fracture. Continuous maintenance and transformation of striking platforms and primary reduction surfaces are essential to most core reduction strategies. Aspects of core reduction that reflect dynamic decision making processes are difficult to model from a geometric standpoint, though the models do suggest some clear implications regarding their operation. It is likely that the degree of efficiency and flexibility exhibited by steep angle cores in initial preparation also will characterize subsequent stages of platform and primary surface maintenance. Because changing platform location does not have drastic consequences for overall efficiency it may be easier to correct serious reduction errors. Moreover, steep angle, Levallois-like core geometries may minimize serious reduction errors by limiting the amount of necessary preparation and hence the number of technical operations in which errors might occur (Brantingham *et al.*, 2000). At the same time, high levels of productivity should be sustained by continuing with steep angle core preparation throughout all stages of core reduction. Of course, these hypotheses require additional modelling and testing.

The models also assume that the primary reduction surface can be adequately prepared for the production of blanks within the spatial constraints defined by the position and angle of the platform. This is realistic only where organized flaking surfaces can be achieved with a minimum of preparation, a situation which pertains in a surprising range of archaeological situations (e.g., Brantingham *et al.*, 2000; Kuhn, 1995*b*). If the desired endproducts must meet very strict requirements of shape, size and character, thereby placing substantial demands on preparatory shaping of core surfaces (Baumler, 1995: 17), then some aspects of these models become increasingly unrealistic. With more design flexibility in terms of blank morphology it should be easier to meet the geometric parameters suggested by the models.

To make realistic archaeological predictions it is also important to point out that the differences in core efficiency and productivity suggested by these models are for cores based on initial cobbles identical in all respects. In reality, no two pieces of stone raw material will be the same exact size and shape and rarely will they possess the exact same internal structure (Baumler, 1995: 13). Thus, any archaeological application of these models must be flexible enough to deal with variability introduced by differences in initial blank size, shape and quality.

Despite these limitations, the implications of these models for understanding the economy and ecology of Levallois core technology are significant. Optimization of any system often involves serious tradeoffs, where one potentially beneficial attribute or process is maximized at the expense of one or more alternatives. One implication of the mathematical models developed here is that Levallois core technology is not so seriously constrained. Rather, Levallois core technology appears to capable of simultaneously minimizing raw material waste and maximizing blank production and the generation of usable cutting edge. It also is quite flexible in how raw material efficiency is achieved. On the other hand, changing one aspect of core morphology, platform angle, lowers efficiency and exaggerates tradeoffs between waste generation and core productivity. With acute angle cores one must apparently choose to either minimize raw material waste, or maximize core productivity; it is exceedingly difficult to optimize both currencies.

In ecological and evolutionary systems, where tradeoffs are most often the rule, coinciding optima such as exhibited by this model of Levallois are of the greatest importance. Increased efficiency in managing raw material waste means that individual cores may have had low associated production costs, whether measured in terms of preparation time and effort directly at a quarry site (e.g., Van Peer, 1998), or in terms of the risks and transport costs associated with core reduction at points away from localized raw material sources (e.g., Henry, 1995: 187). In either case, the low level of preparation waste attributed to Levallois core technology may have served to untether foraging patterns from spatially fixed stone raw material sources. Time saved in core preparation and flake production at a quarry site, for example, translates into time saved in retooling and greater time available to invest in foraging and other activities. This time efficiency is enhanced if the properties exhibited by Levallois technology during initial preparation continue through repeated stages of core maintenance.

The productivity of Levallois cores in terms of both number of blanks and cumulative cutting edge length also holds important behavioural and ecological implications. Raw material efficiency in the preparation stages need not necessarily translate into high core productivity: a core technology very efficient during initial preparation could thereafter generate only a few large blanks and a limited amount of cutting edge per unit volume. Yet in the case of Levallois core technology, the point of greatest raw material efficiency coincides with increased blank production and maximum cutting edge. Levallois cores may provide a relatively efficient source of tool blanks for reprovisioning the active toolkit. Since levels of mobility are thought to be linked to both blank morphology (e.g., Kuhn, 1994) and the ability to generate usable cutting edge (e.g., Henry, 1995), Levallois core technology may directly facilitate high mobility by maximizing both of these currencies.

The models also show the detrimental consequences of permitting core reduction to drift away from an ideal Levallois geometry. Making similar cores with more acute platform angles may result in decreased productivity, more preparation waste, and a lesser degree of flexibility in where platforms are placed. Thus, while it is possible in principle to depart from the basic set of features that are now used to define Levallois, there are disadvantages to doing so. These economic consequences offer sufficient grounds for invoking a form of stabilizing selection that would push core reduction strategies back towards a Levallois format when attributes such as platform angle and position deviated from their optimal configurations.

Although there are many potential economic benefits surrounding the use of Levallois core reduction strategies, there is nothing *inevitable* about the adoption of Levallois core reduction strategies. It remains difficult to fully delineate the mechanisms that led to the initial adoption of Levallois reduction strategies over other potential alternatives (e.g., bifaces, blades, simple cores and flakes). Historical factors certainly must be considered. Moreover, the use of Levallois core reduction does not preclude the use of other core technologies. In most archaeological contexts we are often dealing with a question of the relative frequency of Levallois core reduction strategies within a more varied lithic technological system, rather than simply the presence or absence of such. We are in the process of developing simulation models that will accurately represent these assemblage-scale complexities, facilitating comparisons of the costs and benefits of different core technologies used in tandem.

In the absence of these more complex models and comprehensive archaeological tests, one might still argue that the adoption of Levallois technology is largely arbitrary and therefore reflects the "behavioural phylogeny" of a particular hominid species. While this type of phylogenetic link might be possible, the growing number of examples of direct associations between specific hominid taxa and supposedly "incongruent" stone technologies dictate caution (e.g., Bar-Yosef & Kuhn, 1999; Lévêque, 1993; Mercier *et al.*, 1993). Moreover, any assignment of phylogenetic significance of Levallois-Mode III core technologies should first exclude this possibility of behavioural convergence as a result of mechanical and economic factors. The economic advantages inherent in Levallois core geometries, and the disadvantages of deviating from this basic plan, suggest that they may constitute an "adaptive peak" within a broader landscape of alternative technological strategies (see Futuyama, 1986: 255). Convergence on this "adaptive peak" simply as a function of continuous drift in core reduction strategies is not unlikely, especially if hominid foraging groups are exposed to a common suite of selective pressures. Convergences in behaviour, anatomy and physiology are quite common among distantly related (and geographically isolated) animal taxa exposed to similar selective pressures (Futuyama, 1986; see also Brantingham, 1998*a*, 1998*b*). The environmental and situational contexts that might render it advantageous to minimize raw material wastage in core preparation while maximizing edge production are numerous indeed (e.g., Andrefsky, 1994; Bamforth, 1986; Brantingham *et al.*, 2000; Kuhn, 1994, 1995*a*). It is very unlikely that such selective pressures were unique to one particular hominid taxon and not others. Levallois core reduction strategies (as one potential response to these pressures) are similarly unlikely to have been linked exclusively to a single hominid taxon.

A number of authors have considered, and in some cases dismissed, the possible cognitive implications of the global uniformity in the basic characteristics of Levallois technology (see Boëda, 1995; Chazan, 1997; Noble & Davidson, 1996; Dibble & Bar-Yosef, 1995). One implication of the models presented here is that some features common to Levallois technology (i.e., maintenance of steep platform angles) could simply reflect common pressures favouring efficiency in raw material exploitation, rather than shared conventions of core design. The "optimization" of core reduction behaviours does not immediately imply complex cultural mechanisms or complex cognitive templates. On the contrary, a variety of organisms ranging from insects to birds and rodents engage in behaviours consistent with such optimizing principles, all in the apparent absence of human-like "culture" and cognitive abilities (see Stephens & Krebs, 1986; Vander Wall, 1990). However, we do not intend to discount the possible cognitive significance of all aspects of this remarkable technological phenomenon. In searching for unique cognitive signals in the record of ancient behaviour it is important to first isolate what may be attributable to more mundane economic or mechanical factors. Many other features of Levallois technologies, such as the manner in which platform angles and the convexities of the face of detachment are achieved and maintained, are not so obviously subject to mechanical constraints.

Conclusions

The models developed here move discussion of Levallois technology in the direction of evolutionary perspectives. It is important to emphasize that such models can only serve as sources of hypotheses. They are not intended to accurately represent past behaviour, but rather to make our ideas about that behaviour more explicit and more testable. Nevertheless, the models presented above hold several important implications for understanding the appearance, spread and temporal persistence of Levallois core reduction strategies. The features of Levallois core geometry, in particular the angular relationship between striking platform and core face, offer one potential means of simultaneously minimizing waste and maximizing high core productivity. The repeated occurrence of Levallois core technologies in a wide range of archaeological contexts may reflect similar pressures with respect to the efficient conversion of raw material into usable blanks. Evolutionary convergence and stabilizing selection may thus have played a large role in maintaining the remarkable "uniformity" of Levallois core geometries over vast tracts of time. Phylogenetic links between Levallois-Mode III and particular hominid species are not impossible, though they are probably relatively unimportant compared with the potential economic and ecological roles played by stone tool technologies in hominid foraging adaptations.

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