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# Defining and measuring reduction in unifacial stone tools

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**Abstract**

Observations pertaining to particular stages of the lithic *chaîne opératoire*, or reconstructions of the entire operational sequence at a particular site, can be used to develop a detailed understanding of past human cognitive capabilities, technological sophistication, mobility, and land use. The "*reduction sequence*" is a specific stage of the *chaîne opératoire* that many archaeologists have attempted to measure. Many of these attempts fail to recognize that "reduction" is a three-dimensional process, and thus should be measured with an appropriate three-dimensional unit: volume. This paper presents a new methodology for measuring and defining reduction in unifacial stone tools that reconstructs the original volume of a modified blank, allowing a realistic percentage of volume loss to be calculated. This new method is fast, precise, and very accurate.


*Keywords:* Lithic technology; Reduction sequence; *Chaîne opératoire*; Unifacial stone tools; Experimental archaeology

## 1. Introduction

An important concept to the study of lithic assemblages is the *chaîne opératoire*, or the "operational sequence" [9,41,46,53,55]. This concept is based on the recognition that there are many stages in the "life histories" of artifacts, starting with the procurement of raw materials and ending with the final abandonment of the object [4,9,10,25,34,37,45,48]. The concept of a "*reduction sequence*", when applied to either core reduction or artifact resharpening, represents a specific stage of the *chaîne opératoire* that itself is composed of several sub-stages, such as core preparation (decortication), blank production, core reshaping, retouched tool manufacture, and resharpening [18]. This entire process of stone tool production, combined with the initial stage of raw material acquisition and the terminal stages of tool use and discard, defines the *chaîne opératoire*. Observations pertaining to particular stages of lithic *chaîne opératoire*, or reconstructions of the entire operational sequence at a particular site can be used to develop a detailed understanding of past human cognitive capabilities [27,29,57,63], technological sophistication [8,32,35,38,40,47], site formation [51], and mobility and land use [38,50,52,58–61].

The process of stone tool production is inherently reductive, as it involves the loss of mass and volume from the original piece being modified. This reduction of mass/volume occurs in two main contexts:

(1) Core reduction, which includes core preparation, blank removal, and core repreparation.

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(2) Tool production, which involves blank retouching, resulting in the modification of blank shape via the removal of mass/volume.

This second category of reduction, that is the progressive modification of artifacts through retouch and resharpening, is central to assessing the length and complexity of artifact ''life histories'', as well as the effects of raw material availability. For example, artifacts made on exotic raw materials procured from sources located tens of kilometers from their eventual area of discard tend to be more extensively reduced than artifacts produced on immediately available materials [1,14,24,26,37,38,49]. Two key concepts related to artifact life histories are ''curation'' and ''expedience'' [5,6,43,54]. With respect to lithic assemblages the degree of curated or expedient behavior in raw material procurement, tool manufacture, use and discard has traditionally been associated with the intensity of tool reduction and tool size. As a result, many archaeologists have attempted to develop methods of measuring levels of tool reduction accurately and reliably [2,3,7,11–13, 15–23,28,30–33,36–39,42,44,56,62]. While substantial effort has been made to understand and quantify stone tool reduction and artifact use-lives, researchers have yet to develop a suitable method that satisfies the needs of most researchers; thus it is clear that ample room exists for considerable methodological improvements. In this paper, we propose a new technique for measuring levels of artifact size reduction as a result of unifacial retouch. This novel approach builds upon important aspects of previous methods while avoiding some of their limitations.

One set of approaches to evaluating the extent of retouched tool reduction is based on the estimates of original blank mass. Pelcin [44] defines tool reduction as the amount of mass that has been removed during the retouching process. Thus, ''flake mass is the most useful measurement for the determination of tool retouch and curation'' [44]. Comparison of the remaining mass with the estimated original mass is used to estimate the amount of material removed during retouch. Unfortunately, accurate estimates of original blank mass can be difficult to obtain. Variables such as platform depth and exterior platform angle [20,44] and platform width [15] have been employed to calculate estimates of blank mass. However, based on these measures, the accuracy of the resulting estimates remain disputed, especially when they are applied to archaeological rather than experimental assemblages [15,19,44].

Kuhn [36] devised an alternative approach, estimating retouch intensity or ''reduction'', known as the geometric Index of Reduction (IR) for unifacial stone tools. His equation, index, $I=(D)\sin(a)/T$, ''is largely free of assumptions about the nature of reduction sequences'' [36] where the ratio of the maximum medial thickness of the unifacial tool ($T$) to the vertical thickness of the flake at the terminations of the retouch on the unifacial tool ($t$) is easily found through the variables depth of retouch scars ($D$), angle of retouch ($a$), and ''$T$''. The IR has proven to be a very useful measurement, but it is also an incomplete one. Below are two hypothetical scenarios that question the utility of this index as a measure of tool reduction:

(1) Let us assume that two unifacial tools of similar size both have an IR of 0.5. The first tool is retouched on 40% of its edges, while the second tool is retouched on 80% of its possible edges. If reduction is defined as the process by which mass/volume is lost, it is obvious that the tool retouched on 80% of its edges with an IR of 0.5 is more reduced than the tool retouched on 40% of its edges with and IR of 0.5. The IR alone makes no distinction between these two tools even though one has experienced greater reduction.
(2) Let us assume that one unifacial tool is three times as large as another. The larger tool has an IR of 0.6 on 30% of its edges while the second, smaller tool has an IR of 0.5 on 90% of its edges. Kuhn's IR indicates that the larger piece is more reduced, however, without a way to estimate the actual amount of debitage lost in relation to the original unmodified blank, it would be hard to determine which tool has actually lost more mass/volume, and hence, which piece is more reduced relative to original blank size.

It has also been suggested that the IR may be biased by the cross-sectional morphologies of flakes, so that it does not produce comparable results between flakes of radically different shapes [18,36]. However, it has recently been demonstrated that this 'flat-flake' criticism [18] does not pose as a substantial problem [31]. Finally, the IR works only on sidescrapers, where the retouched edge gradually approaches the thickest (medial) part of the flake as retouch advances. The IR would probably not work as well for endscrapers, although this hypothesis has not been tested.

Kuhn's IR measures reduction (defined here as loss of mass) only indirectly. What it really assesses is the position of the retouched edge relative to the spine of a tool, which is the amount of the blank's original width that has been lost. One of the inherent limitations of the IR as an indicator of reduction is that it is elaborated from cross-sectional geometry on a bi-dimensional (2D) basis. Volume and mass, directly proportional by density, are three-dimensional (3D) phenomena. As will be explained below, this distinction clarifies what the IR truly measures.

To overcome the incompleteness of the original IR, we propose a new approach to evaluating the loss of mass/volume among tools retouched unifacially. Our approach is geometric in nature, but it treats artifact size and shape in three, rather than two dimensions. In addition, and as in the approaches outlined above, this new geometric method is used to quantify mass/volume loss relative to the original unmodified blank. In this respect, our method combines the best elements of previous attempts at measuring levels of reduction in unifacial artifacts. There are limitations to our method though, which are elaborated on towards the end of this paper.

## 2. Method for calculating reduction

Finding the mass/volume of the missing debitage resulting from the reduction of a given artifact is a mathematical process. The application of retouch modifies a blank beginning around its edges and continues towards the center. The amount of the mass that is lost through reduction can be evaluated from a three-dimensional perspective as indicated in Figs. 1–9.

Fig. 1 shows a cross-section of a retouched unifacial scraper. As discussed above "$T$" is the maximum medial thickness of the piece, "$D$" is the retouch length and "$\angle a$" is the retouch edge angle [36]. The goal is to determine the amount of mass/volume that has been lost. To achieve this we need to estimate the amount of material that has been removed from the original blank.

In order to calculate the mass/volume of the debitage removed (Fig. 2), a triangle with area "$A$" and sides $D$, $D_1$, and $D_2$ is drawn. "$A$" represents the amount of debitage that has been removed from an infinitely thin "slice" of a unifacial scraper. To calculate the mass/volume "$V$" of the missing debitage, we multiply the "$A$" by the length of the edge that is retouched ($L$). But first, "$A$" must be found.

Drawing the triangle with area "$A$" requires extending the dorsal plane and the ventral plane until they

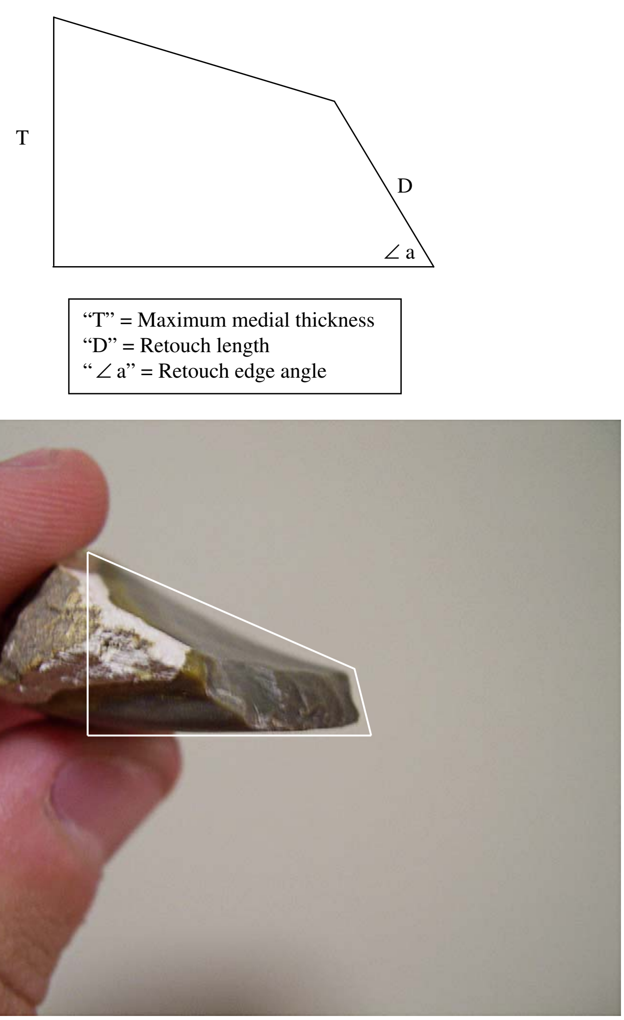


Fig. 1. Cross-section of a retouched unifacial scraper.

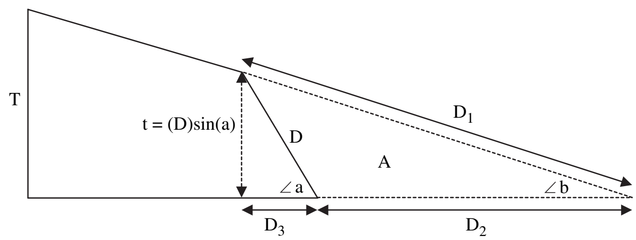


Fig. 2. Hypothetical triangle with sides "$D$", "$D_1$", "$D_2$", and area "$A$" drawn onto unifacial scraper cross-section.

meet and form the dorsal plane angle $\angle b$. Also, we know from Kuhn [36] and from trigonometry that

$$t=(D)\sin(a),$$

because

$$\sin(\Theta)=\frac{\text{opposite}}{\text{hypotenuse}}.$$

In this case, $\Theta=\angle a$, hypotenuse = $D$, and opposite = $t$. The next step is to find "$D_3$" (Fig. 3). "$D_3$" is found using

$$\cos(\Theta)=\frac{\text{adjacent}}{\text{hypotenuse}},$$

with $\Theta=\angle a$, hypotenuse = $D$, and adjacent = $D_3$. So

$$D_3=(D)\cos(a).$$

"$D_1$" (Fig. 4) is found by again knowing that

$$\sin(\Theta)=\frac{\text{opposite}}{\text{hypotenuse}}.$$

In this case $\Theta=\angle b$, opposite = $t$, and hypotenuse = $D_1$. So

$$D_1=\frac{t}{\sin(b)}.$$

Now "$D_4$" (Fig. 5) must be found. $D_4$ is found by

$$\cos(\Theta)=\frac{\text{adjacent}}{\text{hypotenuse}}.$$

$\Theta=\angle b$, hypotenuse $=t/\sin(b)$, and adjacent = $D_4$. So

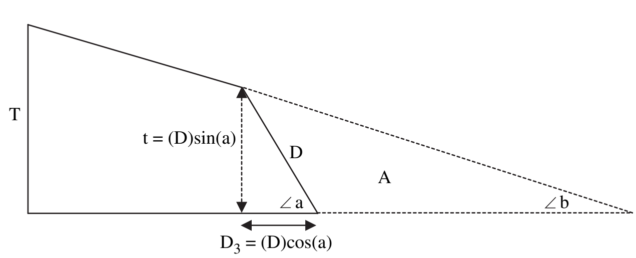


Fig. 3. Calculation of $D_3$.

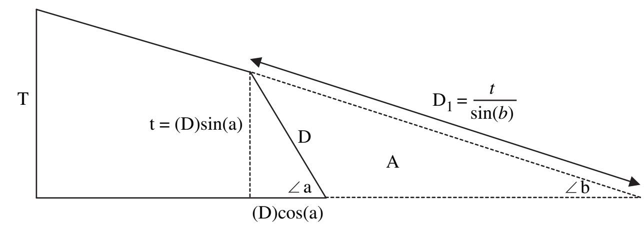


Fig. 4. Calculation of $D_1$.

$$D_4=\frac{t\cos(b)}{\sin(b)},$$

which can be simplified to

$$(t)\cot(b),$$

because

$$\cot(\Theta)=\frac{\cos\Theta}{\sin\Theta}.$$

"$D_2$" (Fig. 6) can now be found by subtracting "$D_3$" from "$D_4$". Since we already know these values, this is a simple task:

$$D_2=D_4-D_3=(t)\cot(b)-(D)\cos(a).$$

Now we must find height "$h$". Recall that the area of a triangle is

$$\frac{1}{2}(\text{base})\ (\text{height}).$$

To find height "$h$" (Fig. 7), define base "$B$" as:

$$\text{“}B\text{”}=D_1=\frac{t}{\sin(b)}.$$

Now use:

$$\sin(\Theta)=\frac{\text{opposite}}{\text{hypotenuse}},$$

where $\Theta=B$, hypotenuse = $D_2$ = $(t)\cot(b)-(D)\cos(a)$, and opposite = $h$. So,

$$h=\sin(b)((t)\cot(b)-(D)\cos(a)).$$

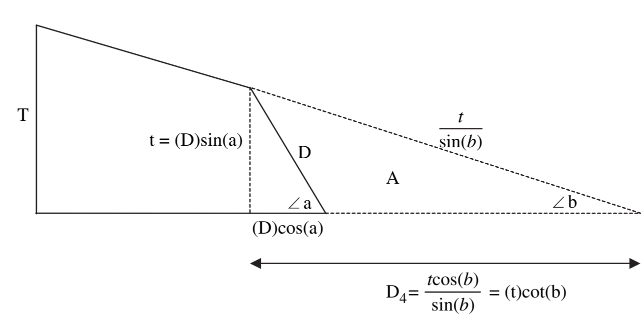


Fig. 5. Calculation of $D_4$.

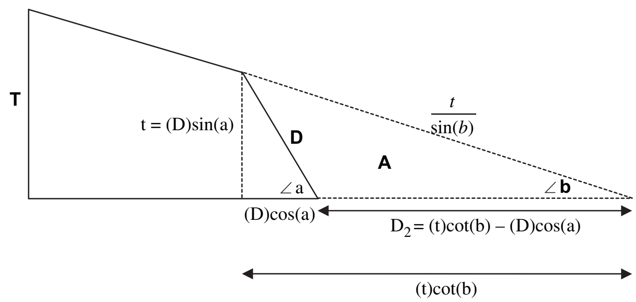


Fig. 6. Calculation of $D_2$.

We now have all the values needed to find area $A = 1/2(B)(h)$. So,

$$A = \frac{1}{2}\left(\frac{t}{\sin(b)}\right)(\sin(b)((t)\cot(b) - (D)\cos(a))),$$

which can be simplified to

$$A = \frac{1}{2}(t)((t)\cot(b) - (D)\cos(a)).$$

Recall that $t = (D)\sin(a)$. With this fact in mind, the final equation for calculating the area of missing debitage is

$$A = \frac{1}{2}(D)\sin(a)((D)\sin(a)\cot(b) - (D)\cos(a)),$$

which can be simplified to

$$A = \frac{D^2}{2}\left(\sin^2(a)\cot(b) - \sin(a)\cos(a)\right).$$

To find the estimated volume "$V$" of the debitage missing, simply multiply the area "$A$" by the length of the retouched edge "$L$" (Fig. 8). If retouch on the specimen is discontinuous, simply measure the length of each retouched segment and add them together.

So, the Reduction Equation (RE) is

$$V = L\frac{D^2}{2}\left(\sin^2(a)\cot(b) - \sin(a)\cos(a)\right).$$

The value "$V$" estimates the volume of debitage removed from a unifacial tool (VolumeEstimatedDebitage).

In order to find the Estimated Reduction Percentage (ERP) in relation to the original unmodified blank, measure the volume of the retouched tool by putting it in water and measuring the volume displacement (VolumeRetouchedPiece). Then divide

$$\frac{\text{VolumeEstimatedDebitage}}{\text{VolumeEstimatedDebitage} + \text{VolumeRetouchedPiece}}.$$

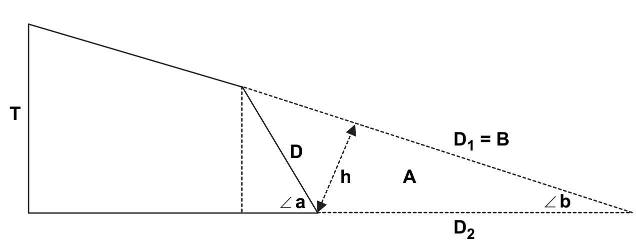


Fig. 7. Calculation of area $A$. Triangle area = 1/2(base)(height). Base $B = D_1$.

## 3. Test replication

A sample of 50 blanks was reduced to different degrees and analyzed using the method described above (Table 1). The test sample consisted of specimens retouched on their lateral edges (37 specimens) and specimens retouched on their lateral and distal edges (13 specimens). As seen from Table 1, there were a variety of blank sizes used. Blank curvature in some cases was very pronounced, while in other cases did not exist at all. While many of the specimens exhibited a triangular cross-section, there were blanks with smooth, rounded dorsal sides and blanks with flattish dorsal sides. Retouch was sometimes regular, though often it was irregular, with heavy retouch on one part of the specimen and light retouch on another part of the same specimen. All samples were stored in the Peabody Museum of Archaeology and Ethnology, Harvard University. At first glance, the complexity and length of the RE equation might discourage its use among archaeologists. In order to rectify this problem, we typed the RE equation as a PC-based algorithm into the computer program Microsoft Excel. This way, long and complicated computational work was avoided and results were achieved with minimal time-commitment. Mitutoyo Digimatic Calipers, a Ha We Contact Gonimeter, a Ohaus CT 1200 Portable Advanced Digital Scale, a 1000 mL Pyrex Beaker, and a 500 mL Kimble graduated cylinder were used to obtain the critical measurements. Tests of the Reduction Equation (RE) and the Estimated Reduction Percentage (ERP) involved the following procedure:

Step 1 The mass of an unmodified flake was measured by placing it on a scale.

Step 2 The volume of the unmodified flake was determined by placing it in a beaker or graduated cylinder and measuring the displaced volume. To get the most precise estimate, the radius ($r$) of the beaker was measured with calipers. The height ($h$) of water displacement due to the immersion of the flake was also measured with calipers. Then the equation for the volume of a cylinder $V = \pi r^2 h$ was used to find the volume of the unmodified flake.

Step 3 Eren and Dominguez-Rodrigo retouched each piece via hard-hammer percussion.

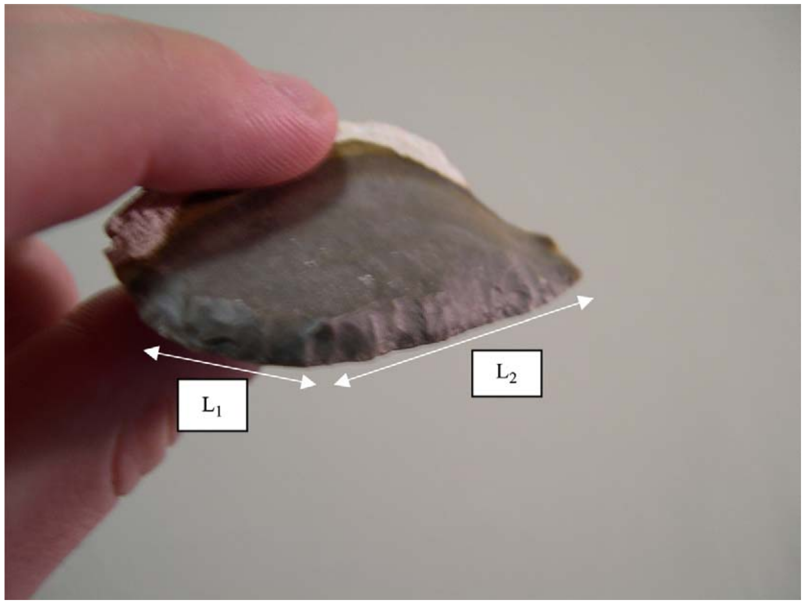


Fig. 8. Example of estimated length of retouched edge $L$. In this particular scenario, $L = L_1 + L_2$.

Step 4 The mass of the modified flake was measured as above.

Step 5 The mass of the debitage was found by subtracting the mass of the modified piece from that of the unmodified piece.

Step 6 The volume of the modified flake and the debitage was found by using the equation Density = Volume/Mass. The density of the piece does not change after reduction has taken place, thus a simple proportion can be used to find the volume of the modified flake and the debitage:

$$\frac{\text{Volume}_{\text{unmodified}}}{\text{Mass}_{\text{unmodified}}} = \frac{\text{Volume}_{\text{modified}}}{\text{Mass}_{\text{modified}}},$$

$$\frac{\text{Volume}_{\text{unmodified}}}{\text{Mass}_{\text{unmodified}}} = \frac{\text{Volume}_{\text{Debitage}}}{\text{Mass}_{\text{Debitage}}}.$$

Fig. 9. When irregular retouch is present, many values of "$a$", "$b$", and "$D$" are recorded on several points along the tool edge. These values are then averaged.

Table 1
Data for experimental analysis

| # | Unmodified | | Retouched | | Control | | Control results | Test variables | | | | | | Test results | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mass | Volume | Mass | Volume | Mass | Volume | RP | *T* | *a* | *D* | *b* | *L* | RE | ERP | RP − ERP | IR |
| 1 | 244.9 | 96.14 | 228.4 | 113.21 | 16.5 | 6.47 | 0.0667 | 24.02 | 64.75 | 14.26 | 37.33 | 76.52 | 5.32 | 0.0384 | 0.0283 | 0.5367 |
| 2 | 58.3 | 26.65 | 52.6 | 24.04 | 5.7 | 2.90 | 0.1088 | 12.69 | 70.83 | 7.64 | 36.66 | 94.13 | 2.43 | 0.0918 | 0.0170 | 0.4077 |
| 3 | 310.9 | 122.74 | 272.9 | 107.74 | 38.0 | 15.00 | 0.1222 | 25.51 | 71.00 | 23.04 | 47.00 | 113.22 | 15.80 | 0.1279 | −0.0057 | 0.8539 |
| 4 | 128.1 | 47.80 | 118.2 | 44.11 | 9.9 | 3.69 | 0.0772 | 20.53 | 74.14 | 8.92 | 52.33 | 127.35 | 1.17 | 0.0258 | 0.0514 | 0.4179 |
| 5 | 227.4 | 87.66 | 206.5 | 79.60 | 20.9 | 8.06 | 0.0920 | 25.15 | 63.00 | 19.19 | 44.25 | 105.00 | 7.94 | 0.0907 | 0.0013 | 0.6799 |
| 6 | 121.1 | 44.20 | 107.2 | 39.13 | 13.9 | 5.07 | 0.1147 | 19.72 | 67.71 | 8.35 | 30.66 | 97.11 | 3.67 | 0.0857 | 0.0290 | 0.3917 |
| 7 | 193.5 | 74.40 | 160.1 | 61.69 | 33.4 | 12.84 | 0.1726 | 18.80 | 67.40 | 13.08 | 43.83 | 197.00 | 8.98 | 0.1260 | 0.0467 | 0.6423 |
| 8 | 131.8 | 46.75 | 109.1 | 38.70 | 22.7 | 8.05 | 0.1722 | 20.08 | 59.60 | 13.48 | 36.25 | 101.58 | 2.60 | 0.0630 | 0.1093 | 0.5788 |
| 9 | 215.0 | 84.74 | 187.4 | 73.83 | 27.6 | 10.88 | 0.1284 | 31.68 | 60.80 | 21.26 | 42.75 | 121.70 | 11.44 | 0.1342 | −0.0058 | 0.5859 |
| 10 | 33.9 | 13.80 | 31.1 | 12.66 | 2.8 | 1.14 | 0.0826 | 16.50 | 56.00 | 5.14 | 23.40 | 57.34 | 0.85 | 0.0629 | 0.0197 | 0.2582 |
| 11 | 116.9 | 47.45 | 89.1 | 36.17 | 27.8 | 11.28 | 0.2377 | 23.70 | 66.77 | 13.84 | 35.42 | 153.41 | 12.12 | 0.2510 | −0.0133 | 0.5366 |
| 12 | 73.5 | 27.09 | 61.1 | 22.52 | 12.4 | 4.57 | 0.1687 | 20.39 | 71.85 | 10.49 | 35.60 | 85.18 | 4.52 | 0.1672 | 0.0015 | 0.4889 |
| 13 | 77.3 | 27.46 | 71.2 | 25.29 | 6.1 | 2.17 | 0.0790 | 20.47 | 84.00 | 14.14 | 35.20 | 69.94 | 9.08 | 0.2642 | −0.1852 | 0.6869 |
| 14 | 126.1 | 46.46 | 109.9 | 40.49 | 16.2 | 5.97 | 0.1285 | 26.73 | 73.75 | 11.43 | 38.16 | 127.56 | 4.44 | 0.0988 | 0.0297 | 0.4105 |
| 15 | 174.1 | 58.15 | 153.0 | 51.10 | 21.1 | 7.05 | 0.1212 | 28.34 | 63.86 | 15.78 | 37.50 | 101.38 | 8.26 | 0.1392 | −0.0180 | 0.4999 |
| 16 | 69.9 | 26.06 | 62.6 | 24.00 | 7.5 | 2.83 | 0.1086 | 14.30 | 66.60 | 8.83 | 40.00 | 87.23 | 2.71 | 0.1015 | 0.0071 | 0.5667 |
| 17 | 10.9 | 4.00 | 10.3 | 3.77 | 0.6 | 0.22 | 0.0550 | 7.86 | 71.71 | 2.56 | 40.25 | 119.98 | 0.30 | 0.0737 | −0.0187 | 0.3092 |
| 18 | 95.1 | 35.04 | 86.1 | 31.72 | 9.0 | 3.32 | 0.0947 | 17.90 | 69.13 | 9.03 | 39.29 | 130.50 | 3.91 | 0.1097 | −0.0150 | 0.4714 |
| 19 | 22.0 | 8.21 | 20.2 | 7.54 | 1.8 | 0.67 | 0.0816 | 13.94 | 64.00 | 6.11 | 39.00 | 49.85 | 0.56 | 0.0691 | 0.0125 | 0.3939 |
| 20 | 9.8 | 3.68 | 9.0 | 3.38 | 0.8 | 0.03 | 0.0082 | 6.81 | 68.00 | 3.58 | 38.88 | 114.91 | 0.53 | 0.1355 | −0.1273 | 0.4874 |
| 21 | 59.1 | 24.43 | 54.1 | 22.36 | 5.0 | 2.07 | 0.0847 | 12.46 | 71.50 | 6.02 | 39.75 | 93.36 | 1.32 | 0.0557 | 0.0290 | 0.4582 |
| 22 | 71.7 | 28.04 | 70.2 | 27.45 | 1.5 | 0.59 | 0.0210 | 23.49 | 79.67 | 6.50 | 61.75 | 69.29 | 0.50 | 0.0179 | 0.0032 | 0.2722 |
| 23 | 2.0 | 6.75 | 1.9 | 6.41 | 0.1 | 0.03 | 0.0044 | 4.35 | 81.67 | 1.09 | 38.80 | 49.18 | 0.03 | 0.0047 | −0.0002 | 0.2479 |
| 24 | 25.5 | 10.80 | 24.3 | 10.29 | 1.2 | 0.51 | 0.0472 | 12.94 | 76.67 | 4.76 | 50.00 | 89.65 | 0.58 | 0.0534 | −0.0062 | 0.3579 |
| 25 | 15.2 | 5.97 | 14.6 | 5.73 | 0.6 | 0.24 | 0.0402 | 8.33 | 61.00 | 4.00 | 39.20 | 74.99 | 0.31 | 0.0513 | −0.0111 | 0.4200 |
| 26 | 36.9 | 14.05 | 33.8 | 12.86 | 3.1 | 1.18 | 0.0840 | 17.57 | 75.00 | 2.62 | 58.33 | 46.06 | 0.05 | 0.0038 | 0.0802 | 0.1440 |
| 27 | 19.3 | 6.88 | 18.6 | 6.63 | 0.7 | 0.25 | 0.0363 | 7.59 | 68.33 | 4.04 | 42.25 | 64.78 | 0.32 | 0.0460 | −0.0097 | 0.4947 |
| 28 | 49.7 | 19.90 | 46.0 | 18.41 | 3.7 | 1.48 | 0.0737 | 21.22 | 68.00 | 8.22 | 41.00 | 63.52 | 1.37 | 0.0693 | 0.0044 | 0.3592 |
| 29 | 10.5 | 4.29 | 10.2 | 4.17 | 0.3 | 0.12 | 0.0280 | 4.80 | 71.00 | 2.03 | 23.16 | 47.56 | 0.17 | 0.0392 | −0.0112 | 0.3999 |
| 30 | 77.7 | 26.29 | 72.5 | 24.53 | 5.2 | 1.70 | 0.0647 | 16.94 | 81.81 | 4.70 | 49.85 | 147.02 | 1.11 | 0.0433 | 0.0214 | 0.2746 |
| 31 | 36.2 | 13.69 | 33.5 | 12.67 | 2.7 | 1.02 | 0.0745 | 13.82 | 65.33 | 6.47 | 29.66 | 75.82 | 1.70 | 0.1183 | −0.0438 | 0.4254 |
| 32 | 67.7 | 56.68 | 63.2 | 52.91 | 4.5 | 3.77 | 0.0665 | 17.51 | 63.66 | 5.50 | 37.00 | 134.81 | 1.36 | 0.0251 | 0.0415 | 0.2815 |
| 33 | 76.3 | 30.21 | 71.3 | 28.23 | 5.0 | 1.98 | 0.0655 | 15.12 | 71.22 | 6.47 | 57.28 | 133.09 | 0.76 | 0.0259 | 0.0396 | 0.4051 |
| 34 | 31.7 | 12.62 | 27.9 | 11.11 | 3.8 | 1.51 | 0.1198 | 10.63 | 66.18 | 5.32 | 40.37 | 135.89 | 1.18 | 0.0960 | 0.0238 | 0.4578 |
| 35 | 24.1 | 8.04 | 22.3 | 7.44 | 1.8 | 0.60 | 0.0746 | 10.77 | 74.75 | 4.85 | 51.00 | 105.41 | 0.62 | 0.0769 | −0.0023 | 0.4345 |
| 36 | 10.1 | 6.32 | 9.4 | 5.88 | 0.7 | 0.44 | 0.0696 | 6.84 | 63.00 | 2.89 | 25.00 | 49.50 | 0.27 | 0.0439 | 0.0257 | 0.3765 |
| 37 | 45.8 | 18.44 | 44.9 | 18.08 | 0.9 | 0.36 | 0.0195 | 13.00 | 59.20 | 11.20 | 44.67 | 65.66 | 1.26 | 0.0653 | −0.0458 | 0.7400 |
| 38 | 3.5 | 0.55 | 3.4 | 5.30 | 0.1 | 0.02 | 0.0364 | 6.97 | 71.00 | 1.91 | 30.00 | 35.54 | 0.08 | 0.0149 | 0.0215 | 0.2591 |
| 39 | 39.2 | 14.95 | 35.9 | 13.69 | 4.0 | 1.53 | 0.1023 | 14.87 | 64.40 | 6.99 | 30.75 | 61.70 | 1.47 | 0.0972 | 0.0052 | 0.4239 |
| 40 | 49.8 | 21.80 | 48.0 | 21.01 | 1.0 | 0.45 | 0.0206 | 13.86 | 66.13 | 7.04 | 51.29 | 110.59 | 0.82 | 0.0376 | −0.0170 | 0.4645 |
| 41 | 49.7 | 20.54 | 46.5 | 19.01 | 3.2 | 1.32 | 0.0643 | 11.07 | 66.37 | 5.63 | 35.33 | 107.94 | 1.40 | 0.0684 | −0.0041 | 0.4659 |
| 42 | 42.1 | 16.98 | 39.5 | 15.93 | 2.6 | 1.05 | 0.0619 | 11.27 | 73.33 | 5.95 | 35.20 | 71.24 | 1.29 | 0.0749 | −0.0130 | 0.5058 |
| 43 | 49.3 | 20.38 | 48.5 | 20.05 | 0.8 | 0.33 | 0.0162 | 16.91 | 77.66 | 3.94 | 62.33 | 71.80 | 0.16 | 0.0080 | 0.0082 | 0.2276 |
| 44 | 37.9 | 14.72 | 35.7 | 13.87 | 2.2 | 0.85 | 0.0577 | 15.71 | 85.66 | 5.19 | 35.20 | 68.11 | 1.22 | 0.0811 | −0.0234 | 0.3294 |

(*continued on next page*)

Table 1 (*continued*)

| # | Unmodified | | Retouched | | Control | | Control results | Test variables | | | | | | Test results | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mass | Volume | Mass | Volume | Mass | Volume | RP | *T* | *a* | *D* | *b* | *L* | RE | ERP | RP − ERP | IR |
| 45 | 77.3 | 25.59 | 69.3 | 22.94 | 8.0 | 2.65 | 0.1036 | 19.78 | 70.00 | 5.67 | 42.85 | 107.60 | 1.09 | 0.0452 | 0.0584 | 0.2694 |
| 46 | 99.1 | 36.81 | 86.7 | 32.20 | 12.4 | 4.61 | 0.1251 | 15.79 | 66.75 | 9.61 | 35.75 | 144.17 | 5.39 | 0.1434 | −0.0183 | 0.5592 |
| 47 | 53.6 | 21.25 | 50.0 | 19.82 | 3.6 | 1.43 | 0.0672 | 20.41 | 74.14 | 9.22 | 53.14 | 82.00 | 1.50 | 0.0704 | −0.0032 | 0.4345 |
| 48 | 49.3 | 18.28 | 45.7 | 16.95 | 3.6 | 1.33 | 0.0727 | 13.80 | 76.76 | 5.52 | 49.50 | 164.30 | 1.47 | 0.0787 | −0.0060 | 0.3894 |
| 49 | 28.1 | 11.74 | 27.6 | 11.53 | 0.5 | 0.21 | 0.0178 | 16.56 | 88.00 | 5.38 | 63.20 | 53.71 | 0.37 | 0.0306 | −0.0128 | 0.3247 |
| 50 | 105.5 | 43.24 | 83.2 | 34.10 | 22.3 | 9.14 | 0.2114 | 21.35 | 65.75 | 14.94 | 42.62 | 151.49 | 8.94 | 0.2078 | 0.0036 | 0.6380 |

Using the equation Density = Volume/Mass to figure out the modified flake and debitage volumes is much more accurate, practical, and quicker than placing either the modified flake or debitage in water.

Step 7 Now the Reduction Percentage (RP) can be obtained by dividing the debitage volume by the unmodified flake volume. This is the control value of the experiment in which the RE and ERP attempt to estimate.

Step 8 The following variables were measured on each modified piece: Dorsal plane angle (*b*), Retouched Edge Angle (*a*), Retouch Depth (*D*), and Retouch Extent (*L*). Due to irregularity of retouch, we found it best to record several values of "*b*", "*a*", and "*D*" at several points along each specimen's tool edge and then average these values for the most accurate estimate (Fig. 9).

Step 9 The variable values were then plugged into the Reduction Equation (RE). The value of the RE gives the estimated debitage volume. To find the Estimated Reduction Percentage (ERP), the estimated debitage volume was applied to following formula:

$$\frac{\text{VolumeEstimatedDebitage}}{\text{VolumeEstimatedDebitage} + \text{VolumeRetouchedPiece}}.$$

Step 10 Compare the true volume and the estimated volume as well as the RP and the ERP.

## 4. Test results

Experimental results indicate that the proposed method is very accurate for estimating the amount of mass/volume lost due to retouch. The control debitage volume and estimated debitage volume, as well as the Reduction Percentage (RP) and the Estimated Reduction Percentage (ERP) have very high Pearson's correlation values (Table 2, Figs. 10–12). The correlation between Modified ERP and RP (4 outliers omitted, Fig. 12) is much more representative of the predictive power of the Reduction Equation (RE) for the following reason. First, two different containers were used for measuring the volume of each piece. The first container was a large beaker (Pyrex 1000 mL, radius 4.313 cm) with increments of 50 mL (50 $cm^3$). The second container was a large graduated cylinder (Kimble 500 mL, radius 2.264 cm) with increments of 5 mL (5 $cm^3$). Due to its larger radius, the first container was used to

Table 2
Pearson's correlations on test and control values

| | Figure | *n* | Pearson's | *P* | $r^2$ |
|---|---|---|---|---|---|
| True volume and estimated volume | 3 | 50 | 0.9086 | 0.0000 | 0.8256 |
| ERP and RP | 4 | 50 | 0.6736 | 0.0000 | 0.4537 |
| Modified ERP and RP: 4 outliers omitted | 5 | 46 | 0.8939 | 0.0000 | 0.7990 |
| Kuhn's IR and RP | 6 | 50 | 0.4277 | 0.0019 | 0.1829 |

measure the volume of larger pieces. Unfortunately, the larger increments on the first container made it much more difficult to find the volume than with the second container. While the volume of most pieces measured in the first container was accurate ($\leq 5\%$), four pieces measured in the first container produced volumes with errors $\geq 6\%$. We are confident that if a larger container with smaller increments had been used, these four pieces would be $\leq 5\%$ error. In other words, inaccuracies result from the intricacy of measuring the volume of the retouched artifact in water, not from any deficiencies in the RE. The cross-sectional morphology of the blanks might be thought to bias the results, but interestingly the four outliers have triangular cross-sections.

Currently, the ERP is being used to analyze the unifacial scrapers from the Paleo Crossing Site, a Paleoindian site in Northeast Ohio. One hundred and seventy scrapers out of 444 have been analyzed using the ERP and the IR. This work is still currently in progress for Eren's thesis.

## 5. Discussion

In order to find the percentage of reduction by retouch on unifacial scrapers, it is necessary to estimate the Dorsal Plane Angle ($b$), the Retouched Edge Angle ($a$), the Retouch Length ($D$), the Length Edge

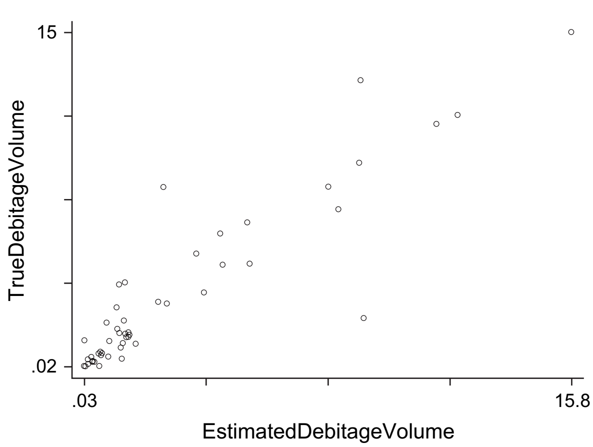


Fig. 10. Pearson's correlation of the True Debitage Volume and the Estimated Debitage Volume (which is given by the RE). Pearson's correlation value = 0.9086.

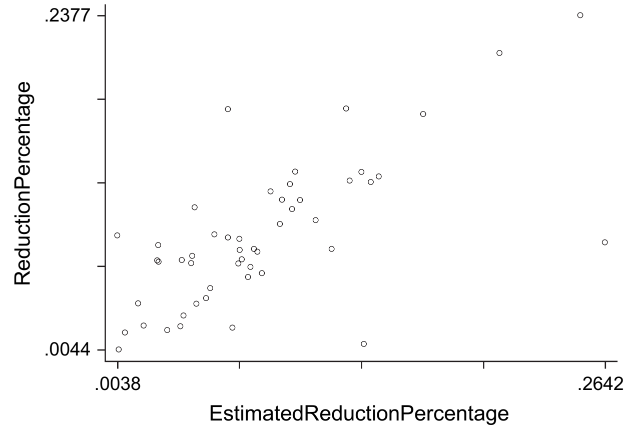


Fig. 11. Pearson's correlation of the Reduction Percentage and the Estimated Reduction Percentage (ERP). Pearson's correlation value = 0.6736.

Retouched ($L$), and the volume of the retouched piece (found through the water displacement). The Reduction Equation (RE) that estimates the volume of debitage removed from a unifacial tool is

$$V = L\frac{D^2}{2}\left(\sin^2(a)\cot(b) - \sin(a)\cos(a)\right),$$

and the Estimated Reduction Percentage (ERP) is

$$\frac{\text{VolumeEstimatedDebitage}}{\text{VolumeEstimatedDebitage} + \text{VolumeRetouchedPiece}}.$$

As outlined above, Kuhn's IR does not measure the reduction of retouched pieces as we have defined it. For this study, the IR was measured at several points along each test specimen's tool edge. These measurements were then averaged. Examination of the data (Table 1) illustrates the discrepancies between the two techniques. For example, the IR for specimen 12 is 0.4889 and the

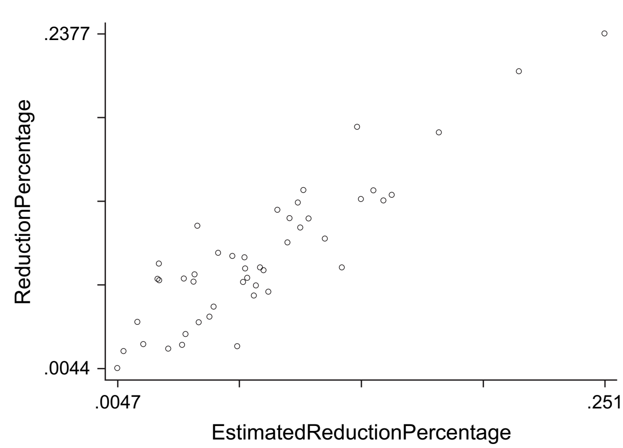


Fig. 12. Pearson's correlation of Reduction Percentage and Estimated Reduction Percentage (ERP) with four outliers omitted. Pearson's correlation value = 0.8939.

IR for specimen 41 is 0.4659. Although the IR for each piece is essentially the same, the ERP is not (specimen 12 = 16.72%, specimen 41 = 6.84%). In other words, specimen 12 has lost more than twice the proportion of its original mass, but the IR makes no distinction.

In another example, specimen 1 (IR = 0.5367, ERP = 3.84%) and specimen 2 (IR = 0.4077, ERP = 9.18%), the highest IR value is assigned to specimen 1 which has actually lost less mass relative to its original size as measured according to our ERP. Using our reduction equation and the ERP, the real reduction is reflected much more accurately: specimen 1 was reduced by 3.84% and specimen 2 by 9.18%.

A correlation was run on the RP (the control of the test) and Kuhn's IR (Table 2 and Fig. 13). These data suggest that Kuhn's IR does reflect reduction to some degree, however, it does not measure accurately the loss of mass or volume, a shortcoming that our method overcomes. Moreover, because our proposed method is not dependant on the measurement of platform attributes in contrast to some other methods [20,21], levels of reduction can be estimated for artifacts with broken, retouched, or thinned platforms, in contrast to previous methods. The distinction between estimating reduction in unifacial scrapers two-dimensionally versus three-dimensionally clarifies what Kuhn's IR measures.

The proposed method does have limitations, though some of these limitations may be rectified through further testing. First, our new approach does not overcome the assumption that the original blank has edges that have feather terminations. Second, our method depends on the fact that the blank is not flat, though theoretically this problem may prove negligible. By measuring the dorsal plane angle "*b*" as very acute on a flat flake, segments $D_1$ and $D_2$ become longer, and thus area "*A*" becomes larger and may more accurately reflect the lost debitage volume. Additionally, the more reduced a unifacial stone tool is, the greater in size a hypothetical triangle with area *A* will be in comparison to the modified tool. Nevertheless, these ideas need to be tested. Third, while our method is quick using a PC-based algorithm, it is not as quick as the IR due to the necessity of recording three additional variables (dorsal plane angle, volume of modified flake, and length of edge retouched). Finally, the accuracy of the RE and ERP should be called into question on specimens that do not exhibit any part of the dorsal surface. This limitation may prove negligible by extending $D_1$ to the termination of retouch scars on the top of the artifact, but this idea also needs to be tested. Other problems that may seem to effect the RE and ERP, such as blank curvature, do not influence the accurateness of our method as long as measurements are recorded carefully at several points along a tool edge and then averaged.

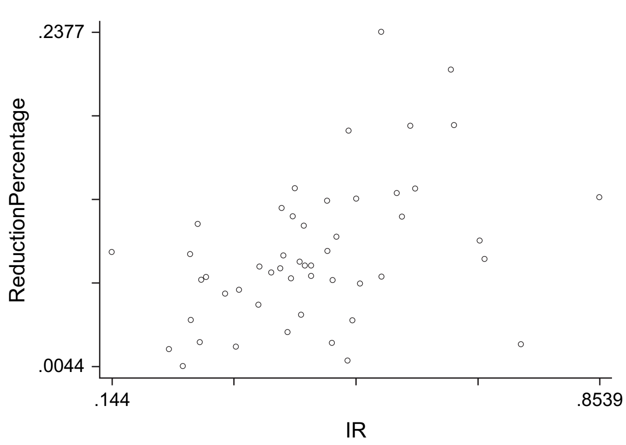


Fig. 13. Pearson's correlation of Reduction Percentage and Index of Reduction (IR). Pearson's correlation value = 0.4277.

We believe that creating mathematical models for reconstructing stone tools three-dimensionally has great potential. Specific three-dimensional models may be possible for other tool types, such as burins. Even though specimens with distal and lateral retouch are included in the RE and ERP test sample, endscraper reduction may be estimated more accurately by three-dimensional models different from the one presented here. Certain bifacial tools that retain parts of their original dorsal and ventral surfaces may also be subject to geometrical reconstruction. Despite the complexity and time-consuming nature these mathematical models might seem to pose, the use of PC-based algorithms allows archaeologists to measure required variables, plug these measurements into a computer, and receive a result with minimal time-commitment. It might also prove possible and interesting to combine various reduction indexes in creative ways to derive even more accurate results, refine or cross-check data, or to overcome deficiencies present in different methods.

The ERP technique proposed here provides a highly precise, replicable, and widely applicable means for measuring the amount of mass/volume an artifact has lost via retouch. As suggested above, the IR actually measures the proportion of artifact width that has been lost by estimating the position of the retouched edge relative to the thickest, central axis of the piece. Which measure is more useful or appropriate? Perhaps neither: both have their uses, and both are relevant to different problems. The question that remains is the degree to which the loss of mass/volume equates with the loss of tool utility (e.g., [54]). Not all of the mass or volume of an artifact is available for use, so not all translates into utility. Another hypothetical example can help to illustrate this. Imagine an artifact, an endscraper for example, which is just under the minimum usable size: the piece still has mass and volume, but it is simply too small to be held in the hand or in a haft. Compare this with another artifact that is twice as large, but has infinitely more utility than the first (which essentially has a utility of zero). In some cases, a linear dimension (length or width) is more directly proportional to utility than mass/volume, whereas in other cases mass/volume best approximates utility. The many techniques proposed for assessing artifact reduction actually measure different things. The IR, RE, and ERP do not portray life histories of stone tools, only the end result of those life histories. Whether mass/volume loss, width loss, or some other attribute is the most appropriate one for answering a particular question about artifact life histories is a separate question from how they should be measured.

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