archaeometry

Archaeometry **61**, 1 (2019) 1–13 doi: 10.1111/arcm.12407

WHY ARE CLOVIS FLUTED POINTS MORE RESILIENT THAN NON-FLUTED LANCEOLATE POINTS? A QUANTITATIVE ASSESSMENT OF BREAKAGE PATTERNS BETWEEN EXPERIMENTAL MODELS*

B. A. STORY,[1] M. I. EREN,[2,3]† K. THOMAS,[1] B. BUCHANAN[4] and D. J. MELTZER[5]

[1]*Department of Civil and Environmental Engineering, Southern Methodist University, Dallas, TX 75275, USA*

[2]*Department of Anthropology, Kent State University, Kent, OH 44242, USA*

[3]*Department of Archaeology, Cleveland Museum of Natural History, Cleveland, OH 44106, USA*

[4]*Department of Anthropology, University of Tulsa, Tulsa, OK 74104, USA*

[5]*Department of Anthropology, Southern Methodist University, Dallas, TX 75275, USA*

*For decades, archaeologists have wondered whether the Clovis Palaeoindian (*c.*11 600–10 800 radiocarbon years* BP*) practice of 'fluting', a flake removal technique that creates a distinctive shallow channel extending from the base of the projectile point towards the tip, bestowed a functional advantage over non-fluted projectile points. Using analytical modelling and static engineering experiments, Thomas* et al. *(2017) found that points that more effectively redistribute stress and relocate damage can absorb significantly more energy, last longer and remain intact relative to points that do not experience these phenomena. In general, stress redistribution and damage relocation is significantly more likely to occur in fluted points, as opposed to non-fluted points, suggesting that fluting acts as a 'shock absorber'. Here, we present a comparative quantitative assessment of breakage patterns between Thomas* et al.*'s (2017) experimental points that shows those experiencing stress redistribution and damage relocation were also able to significantly better resist breakage, and to incur non-catastrophic breaks, than points that less effectively redistribute stress and relocate damage. This more beneficial breakage pattern explains the material advantages provided by stress redistribution and damage relocation, and hence the potential motivation for fluting. This does not preclude the possibility that the process of fluting was accorded significance beyond its possible utilitarian value. Additional tests will be necessary to further resolve the 'shock-absorbing' capabilities of fluting.*

KEYWORDS: STONE TOOLS, ENGINEERING, QUANTITATIVE METHODS, FRACTURE

INTRODUCTION

The Pleistocene history of stone tool technology is marked by innovations both large and small; for example, the emergence of the Acheulean handaxe and its improved ability to cut through materials better than simple stone flakes (Key and Lycett 2017a,b), the invention of the Levallois technique for producing stone flakes with increased use-life, ergonomics and functional effectiveness (Eren and Lycett 2012, 2016; Lycett and Eren 2013a, 2018) and the systematic heat treatment of stone to upgrade its overall workability (Brown *et al*. 2009). These innovations were assuredly not understood by past peoples as modern researchers understand them, in terms of

*Received 1 January 2018; accepted 30 April 2018
†Corresponding author: email meren@kent.edu

engineering principles or quantitative data. Instead, via attentive observation and practical, daily application, prehistoric peoples probably discerned functional differences between stone tool variants. These variants could have arisen via intentional (e.g., deliberate embellishment) or unintentional (e.g., copy error) cultural mutation–generating mechanisms (Lycett 2011; Mesoudi 2011; Schillinger *et al*. 2014). A stone tool variant that provided a functional advantage over other variants would have probably been selected for, transmitted across populations and over generations, and ultimately fixed in a culture's repertoire.

However, tool variants may not have flourished because they provided a functional advantage. For example, as a result of transmission bias, such as copying the tool variant of a prestigious individual (prestige bias), or copying the tool variant most frequent in a population (conformist bias), certain tool forms may spread even though they may not necessarily have provided a functional advantage (Boyd and Richerson 1985; Bettinger and Eerkens 1999; Laland 2004; Mesoudi 2011). Furthermore, as Schillinger *et al*. (2014, 129) describe, even in the absence of transmission biases or selection mechanisms, drift can create cultural macroscale changes and historical patterns through incremental small-scale modifications over time (see also Neiman 1995; Shennan and Wilkinson 2001; Bentley *et al*. 2004; Kohler *et al*. 2004; Lycett 2008; Lycett and von Cramon-Taubadel 2008, 2015; Shennan 2011; Eren *et al*. 2015).

A primary challenge for archaeologists wishing to explain the emergence and evolution of technology is therefore to seek to understand whether certain stone tool variants provide a functional advantage over other variants. If a functional advantage can be demonstrated, then selection can be invoked as an explanation for its evolutionary success.

Why flute?

For decades, archaeologists have wondered whether the practice of 'fluting', a flake removal technique that creates a distinctive shallow channel extending from the base of the point towards the tip (Fig. 1), by Clovis Palaeoindians (*c*.11 600–10 800 radiocarbon years BP) bestowed a functional advantage on their bifacially flaked lanceolate stone projectile points. Both experimental and archaeological evidence suggest that fluting is challenging (Morrow 1995, 2015; Bradley *et al*. 2010; Waters *et al*. 2011; Smallwood 2012), with quantitative estimates from the archaeological record indicating that ~10–20% of points broke during the fluting process (Ellis and Payne 1995). Considering that the time required for an expert knapper to produce a single point is at least 30 min, and this is after what was probably at least 2 years of practice to master the technique (Kelly 2003, 8), it seems reasonable to suspect that there must have been a real or perceived functional advantage to fluting points for Clovis groups to have adopted such a risky and costly technique and then maintained it for multiple generations.

Until recently, however, the purpose of fluting has remained enigmatic (Meltzer 2009). Fluting was originally thought akin to a grooved bayonet, aimed at enhancing the bleeding of a speared animal (Cook 1928), but that hypothesis was soon rejected when it was realized that the flute scars would have been largely buried within the shaft, mastic and haft wrappings (Renaud 1931). Another idea was that fluting enhanced hafting (Cook 1928; Renaud 1931; Roberts 1935). Yet, unfluted projectile points were mounted on spears for millennia without flutes. The possibilities that fluting was done for stylistic or artistic purposes, was a form of costly signalling or served in a pre-hunt ritual (Bradley 1993; Frison and Bradley 1999) are not unreasonable, but such notions are difficult to test; nor do they preclude the possibility that fluting also had a utilitarian function (Meltzer 2009).

Figure 1 *Clovis specimens from the type site, Blackwater Locality 1. These were recovered by John Cotter of the University of Pennsylvania during the 1936 excavations at the site, conducted under the direction of E. B. Howard. Cotter reported that these 'Folsom-like' points (a separate designation of Clovis points had not yet been made, but soon would be, based in part on these specimens) were found in direct association with mammoth bones (Meltzer 2015). Specimens photographed by David J. Meltzer, with the permission of the University of Pennsylvania Museum of Anthropology. [Colour figure can be viewed at wileyonlinelibrary.com]*

One recent proposal suggested that a thinner fluted base—relative to a thicker non-fluted base—acted as a 'shock absorber' at moments of impact, increasing point robusticity and its ability to withstand physical stress via stress redistribution and damage relocation (Thomas *et al*. 2017). The theoretical underpinning of this hypothesis is that specimens under load, such as a Clovis point upon impact, experience stress. Once a specimen's stress limit is reached at a given location, that portion of the specimen will break, or experience crunching or crumpling (akin to the crumple zone of a car), and the stress will be redistributed. If the redistributed stress is below the overall failure stress level, then the specimen will remain intact and may continue to support load; if not, the specimen will fail, sometimes catastrophically. However, depending on the geometry of the specimen under stress, damage may *relocate* from one position on the specimen to another, including from the tip to the base. In terms of Clovis fluted points, Thomas *et al.* (2017) hypothesized that fluted points withstand higher energies and last longer than unfluted points because stress would have been relocated from the tip to the thinner, brittle basal edge that resulted from the fluting. The base would then incur damage until the stress was redistributed once more, with the damage relocated back to the tip, or resulted in the catastrophic failure of the point. This structural gain in point resilience would have provided a selective advantage to foragers on a largely unfamiliar landscape, who were ranging far from known stone sources and in need of longer-lasting, reliable and maintainable weaponry (Thomas *et al*. 2017).

Thomas *et al*. (2017) assessed the 'damage relocation' hypothesis using analytical modelling and experimental tests of fluted and non-fluted specimens. The two types of analytical modelling —static, linear finite element modelling and discrete, deteriorating spring modelling—both supported the idea that fluted points, relative to unfluted points, are more robust and can withstand physical stress better due to the processes of stress redistribution and damage relocation.

The experiments—displacement-controlled axial-compression tests—also supported the hypothesis, albeit not in as straightforward a manner. Initial comparison of fluted- (n = 45) and unfluted-point (n = 15) experimental specimens (of the same stone, size and morphology, save for the occurrence of a flute) showed no statistical difference in energy absorbed before failure, the amount of time before failure or the total length lost before failure. However, upon reexamination of the data, Thomas *et al*. (2017) were able to show that during the physical testing, an occasional unfluted point would crush or fracture at its base by chance and thus incidentally receive the benefits that came with damage relocation. Similarly, on occasion a fluted point would not crush or fracture at its base, and not receive those benefits. These occurrences were exceptions confounding the comparisons.

Thomas *et al*. (2017) therefore subsequently compared all points that experienced damage relocation (n = 31) versus those that did not (n = 29), regardless of whether they were fluted. When examined in this manner, the comparison showed statistically significant advantages in all three variables (energy, time and length) for points that experienced damage relocation, regardless of whether they were fluted. Thus, and consistent with the analytical modelling, the physical experiments showed that damage relocation significantly increases the resilience of points.

Since comparisons of fluted versus unfluted points showed no statistical differences, but comparisons of points with damage relocation versus those without did, it raised a question of frequency: notably, whether fluting significantly increases the chances of damage relocation. It appears that it does. And because damage relocation increases a point's overall resilience in terms of energy absorbed, the time before catastrophic breakage and the ability to remain intact until that moment of breakage, Thomas *et al*. (2017) concluded that fluting conveys a functional advantage.

In sum, the analytical modelling and experimental tests by Thomas *et al*. (2017) demonstrated that fluted projectile points possess structural advantages in overall resilience and the ability to absorb physical stress over unfluted points.

What accounts for the ability of a stone point to redistribute stress and relocate damage?

However, it remains unknown why points that experience stress redistribution and damage relocation can absorb significantly more energy, last longer and remain intact relative to points that do not experience these phenomena. In other words, how and why are these two sets of experimental stone points breaking during load? There are two possibilities: first, upon load stress, points that experience stress redistribution and damage relocation may be more likely to resist breakage, relative to points that do not. Second, points that experience stress redistribution and damage relocation may be more likely to incur non-catastrophic breaks relative to points that do not. Of course, these two possibilities are not mutually exclusive and could theoretically act in concert. To examine this question, we present here a comparative quantitative assessment of breakage patterns among the Thomas *et al.*'s (2017) experimental points that experienced stress redistribution and damage relocation versus those that did not.

MATERIALS AND METHODS

Details of the experimental procedures can be found be found in Thomas *et al.* (2017). Briefly summarizing, the experimental tests were performed on four[1] point model forms, one unfluted and three fluted types (Fig. 2). The points, made of Georgetown chert from Edwards Formation limestone (Texas), were professionally produced with lapidary equipment to be the same size and shape, though varying in flute presence and/or kind. Geometric morphometrics was used to define the composite size and shape. We did not use replicated knapped (chipped) fluted points for the experiment, as it would have been impossible to produce specimens identical in size, shape, fluting and flaking characteristics, thus making it difficult to control for key variables in the experiment.

The points were placed on an Instron 5582 load frame (Fig. 3). The axial compression was performed under displacement control with a constant-rate-of-displacement header moving at $0.01\ \mathrm{mm\,s^{-1}}$. This low header velocity minimizes inertial effects, so that the physical test results can be compared to the static analytical results. Compression continued until the specimen fractured catastrophically and could no longer function as a point, or in such a manner that the geometric support conditions caused the specimen to become unstable in the loading apparatus (Thomas *et al.* 2017).

During the experimental compression testing of each specimen, one of us (K.T.) recorded three kinds of breaks that occurred, as well as the frequency of each kind of break. The first kind of break was called a 'crush', and was indicated by a loud pop, but no observable portion of the point actually broke off. This kind of break is indicative of a point's ability to *resist* breakage. The second kind of break was called a 'small break', and resulted in a flake less than 2.54 cm in maximum dimension breaking off a point.[2] This kind of break is indicative of a point's ability to *incur* non-catastrophic breaks. The third kind of break, a 'large break', occurred when a flake greater than 2.54 cm in maximum dimension broke off a point. This third kind of break was also indicative of a point's ability to incur non-catastrophic breaks, but obviously is potentially more damaging than a 'small break'.

For the analysis here, we compared the number of crushes, small breaks and large breaks between experimental points that experienced stress redistribution and damage relocation (n = 31) versus those that did not (n = 29). These two groups, which include a mix of both fluted and unfluted specimens, were determined by observing which points during the experiment experienced damage relocation before failure—that is, the incurred damage switched from the tip to the base—versus those points that did not. Prior to running statistical analyses, we carried out normality tests on the number of crushes, small breaks and large breaks using Shapiro–Wilk tests. These tests were all significant ($p < 0.000$), indicating that the distributions of these

[1]Due to a typographical error, Thomas *et al.* (2017, 26) mistakenly stated that there were five fluted point models.

[2]The reader may wonder why our cut-off between small and large breaks was 2.54 cm. Engineers in the USA still regularly use inches as a unit of measure, and 1 inch = 2.54 cm. The data recording was already completed when this study was conceived. Future assessments of breakage patterns may profit from assessing breaks between 0 and 1 cm, 1 and 2 cm, 2 and 3 cm, and so on.

Figure 2 *Plan-view (a) and profile-view (b) images of the Clovis point models used in the experiments: unfluted (left); long flute (centre-left); short flute (centre-right); short tapered flute (right). [Colour figure can be viewed at wileyonlinelibrary.com]*

variables do not conform to an underlying normal distribution. Thus, for two-sample comparisons of variables recorded for points with stress redistribution and damage relocation, and those without, we used the non-parametric two-sample Mann–Whitney procedure. The *p*-values for the Mann–Whitney tests were estimated using a Monte Carlo procedure with 9999 permutations. Following the Mann–Whitney tests, we used the Bonferroni method for controlling the false discovery rate. Thus, the significance levels were adjusted according to the number of tests conducted [0.05/(three tests) = 0.0167]. We used the free software PAST 3.01 to conduct the statistical tests (Hammer *et al*. 2001).

Figure 3 *The static, compressive loading set-up using an Instron 5582 axial load frame. [Colour figure can be viewed at wileyonlinelibrary.com]*

RESULTS

The frequencies of each kind of break are presented in Table 1. Points that experienced stress redistribution and damage relocation exhibited more crushes, small breaks and large breaks than those that did not before catastrophic failure. These three variables were compared statistically. However, none of them were normally distributed (crushes, W = 0.7916; $p < 0.0000$; small breaks, W = 0.8992; p = 0.00012; large breaks, W = 0.7312; $p < 0.0000$); hence our use of the non-parametric Mann–Whitney U test. The Bonferroni-corrected alpha level for significance is 0.0167 (as noted).

On average, there were significantly more crushes (U = 241; z = –3.0782; p = 0.0021; Monte Carlo p = 0.0013—Fig. 4 (a)) and small breaks (U = 285; z = –2.499; p = 0.0151; Monte Carlo p = 0.0133—Fig. 4 (b)) for points that experienced stress redistribution and damage relocation than in those points that did not. The number of large breaks, however, was not significantly different between the two data sets (U = 307; z = –2.1446; p = 0.03198; Monte Carlo p = 0.0336—Fig. 4 (c)).

To put these results in broader, non-statistical terms, points experiencing stress redistribution and damage relocation had significantly more crushes on average than points that did not. Because crushes were structural point deformations recognized only via audible ‘pops’, without

Table 1 *Summary statistics of crushes, small breaks, and large breaks for points without, and with, stress redistribution and damage relocation. See figure 4 for box plots*

	Points without stress redistribution and damage relocation (n = 29)			Points with stress redistribution and damage relocation (n = 31)		
	Crushes	*Small breaks*	*Large breaks*	*Crushes*	*Small breaks*	*Large breaks*
Average	22.0	7.8	1.7	32.0	13.4	3.6
Standard deviation	28.2	7.7	2.0	20.3	9.8	4.1
Minimum	1	0	0	5	0	0
Quartile 1	5	1	0	19.5	6	1
Median	14	5	1	25	11	3
Quartile 3	25	12	3	40	19.5	5
Maximum	117	27	6	100	33	20
Range	116	27	6	95	33	20
Interquartile range	20	11	3	20.5	13.5	4

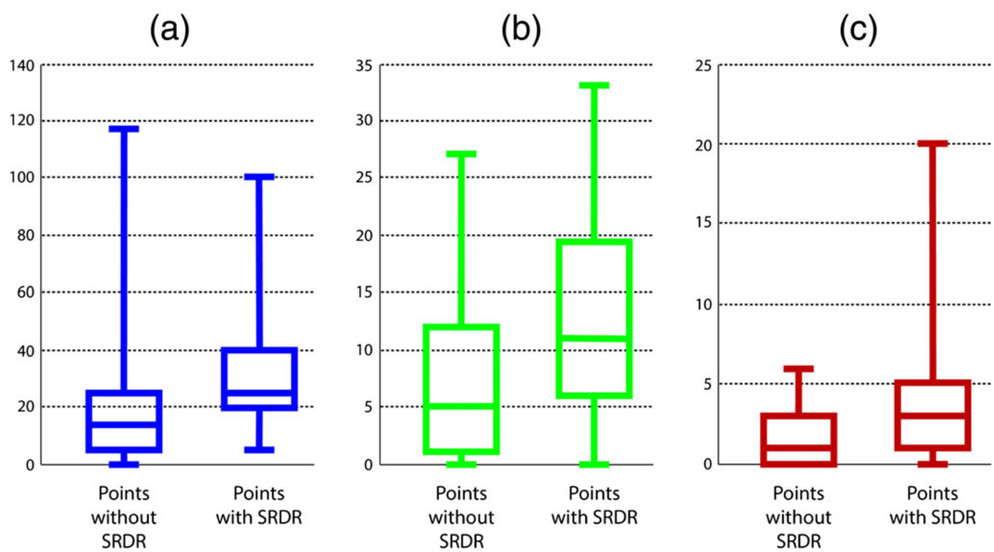

Figure 4 *Box plots of crushes (a), small breaks (b) and large breaks (c) for points without and with stress redistribution and damage relocation (SRDR). For data, see Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]*

any portion of the point breaking off, this result means that under load points experiencing stress redistribution and damage relocation were able to resist breakage better than points that did not. However, points experiencing stress redistribution and damage relocation also possessed significantly more small breaks than points that did not. This result suggests that the former were able to sustain more non-catastrophic breaks than the latter, before the point ultimately failed.

To use a somewhat far-flung metaphor, both fluted and non-fluted points are like boxers that can last 12 rounds of a fight, because they are defensively skilled and mentally and physically tough. But the 'fluted' boxer, who is more likely to experience stress redistribution and damage relocation than the ‘non-fluted’ boxer (Thomas *et al*. 2017), is also more likely to last all 12 rounds because s/he is able to better absorb, deflect and block punches, and at the same time bear a greater number of blows that hit on their mark.

In addition, and as was previously noted, boundary conditions regarding the type and extent of hafting may have influenced the resilience of fluted points and frequency of breakage (Thomas *et al*. 2017, 28). In Thomas *et al*.’s (2017) controlled experiment, the proximal ends of the fluted and unfluted points were subject to three different support conditions: (1) ‘fully engaged’, in which the entire specimen’s basal edge was in contact with the bottom support; (2) ‘partially engaged’, in which the centre of the basal surface was engaged with the bottom support but the outside wings of the point were not in contact; and (3) ‘point support’, in which the experimental point only engaged with a single point load at the centre of the basal edge (Thomas *et al*. 2017, 25, fig. 2b).

These variations in boundary condition served as a way to begin considering different hafting-support conditions. To explore the potential effects of these boundary conditions we here compared the mean number of crushes, small breaks and large breaks between the three sets of points subject to each of these three boundary conditions (data from Thomas *et al*. 2017). We used non-parametric Kruskal–Wallis tests because again the variables did not conform to an underlying normal distribution (Shapiro–Wilk tests indicated p-values < 0.000). For the number of crushes by boundary conditions, the Kruskal–Wallis test indicated a significant p-value ($H = 8.28$; $p = 0.0158$), using a Bonferroni alpha adjustment [$\alpha = 0.05/(\text{three tests}) = 0.0167$]. The Kruskal–Wallis test of small breaks by boundary condition also indicated a significant difference ($H = 11.21$; $p = 0.00361$), driven by a difference between points that were fully engaged and points that had only point support. Lastly, the average number of large breaks was not different across boundary conditions ($H = 1.958$; $p = 0.3603$). Clearly, boundary conditions—that is, the nature of the hafting—also played a role in point breakage (Thomas *et al*. 2017, 28–9).

DISCUSSION AND CONCLUSION

Before labelling Clovis fluted points as some sort of Pleistocene stone tool equivalent to Muhammad Ali’s ‘Rope-a-Dope’ strategy, three sets of analyses (beyond the scope of this study) need to be conducted. These are, first, dynamic tests of fluted and non-fluted points; second, more ‘realistic’ and less controlled (i.e., higher external validity) tests; and, finally, a test of this hypothesis against the archaeological record. We discuss each of these in turn.

Dynamic tests of Thomas *et al*.’s (2017) ‘shock absorption’ hypothesis for the function of fluting should include the thrusting or throwing of experimental points at higher velocities (see Whittaker and Kamp 2007; Whittaker 2010, 2013; Whittaker *et al*. 2017) than the static compression tests used by Thomas *et al*. (2017) ($0.01\ \mathrm{mm\ s^{-1}}$). While stress distribution patterns may not appreciably change in a static versus dynamic scenario—that is, the results of Thomas *et al*. (2017) will probably hold—dynamic analyses and experiments can provide insight beyond expected stress distribution patterns gained from static experiments. Dynamic testing permits the investigation and characterization of the more realistic behaviour of fluted point impacts; specifically, the consequences of different stress magnitudes and energy absorption rates resulting from dynamic loads. Analysis of data from dynamic experiments can also provide more specific insight into the precise mechanisms responsible for the effectiveness of fluting characteristics on specimen endurance. To reiterate, however, we anticipate that the results of Thomas *et al*. (2017) will probably hold: indeed, Dibble and Rezek’s (2009) controlled stone flaking experiments using a mechanical flaking apparatus tentatively support these assertions. They found no difference in flake weight between different displacement speeds of percussors, ranging from 0.01 to 10,000 in min^{-1}. In fact, no morphometric dimensions or dimension ratios exhibited any association with hammer displacement speed, and they noticed no other differences in attributes of flakes resulting from different displacement speeds (erailleur scars, platform lipping or the presence/absence of a point of percussion).

Second, more realistic tests are needed that examine the complex relationship of fluting relative to several variables at once. While more controlled experiments possess certain advantages in repeatability and the ability to manipulate particular variables or parameters in multiple ways, linking findings from controlled experiments to the archaeological record requires the imposition of specific assumptions and inferences that may or may not be valid (Mesoudi 2011; Clarkson *et al*. 2015; Lycett and Eren 2013b; Eren *et al*. 2016). Consider, for example, the approaches of Lipo *et al*. (2012) and Pettigrew *et al*. (2015) on the role of bevelled blade edges. Using fluid-dynamics modelling and controlled wind-tunnel experiments, Lipo *et al*. (2012) suggested that bevelled-edge projectile points would have spun in flight after being launched by hand or from an atlatl, and this in-flight rotation would have increased the accuracy for ballistic shafts. However, Pettigrew *et al*.'s (2015) less-controlled experiments, conducted outdoors using darts launched from atlatls by individuals (and thus more analogous to the behaviour that ultimately produced the archaeological record), suggested that bevelled-edged projectile points do not induce ballistic shafts to rotate in flight. In effect, the complexity and sheer number of variables present in reality—and absent in Lipo *et al*.'s (2012) highly controlled experiments—seem to overwhelm point-edge bevels as the predominant causal factor for in-flight shaft spinning.

Likewise, varying the elements and boundary conditions of fluted projectile points, such as the nature of the haft and the 'pressure' point on the base (as noted above and in Thomas *et al*. 2017), the raw material (Loendorf *et al*. 2018), variations in the width-to-thickness and length-to-thickness ratios (Odell and Cowan 1986; Cheshier and Kelly 2006) and the presence and frequency of flake scars, all must be accounted for in achieving greater analytical realism.

Finally, a test of these ideas must ultimately be set against the archaeological record itself. One possibility would be to compare (microscopically) the basal crushing and the resulting micro-flake scar patterns on Clovis fluted point experimental replicas against those attributes on archaeological specimens (A. M. Smallwood 2015, pers. comm.). Or perhaps preservation conditions at an as-yet-undiscovered Clovis site will be such that the entire Clovis weaponry system—organic and inorganic components—will be recovered and will show whether the haft configuration caused crushing.

If there are shown to be distinctive patterns of crushing and breakage in terms of, say, different hafting-support conditions, that opens up the possibility of using the crushing and breakage of archaeological specimens to hypothesize (essentially, reverse engineer) the nature of Clovis hafting configurations.

Clovis fluting may have arisen through experimentation by Clovis knappers who were intentionally attempting to build a better or more distinctive point, or instead by accident, via a knapping mistake. While the particular reason fluting arose will probably never be known, the question of its widespread adoption and ultimate fixation in the Clovis technological repertoire is one that can be investigated and supported empirically.

Until recently, the lack of evidence for flutes bestowing any functional advantage to stone points seemed to indicate that the practice of Clovis fluting through time and across North America was due to some sort of cultural transmission bias, or perhaps even to drift (Meltzer 2009). However, in light of our results showing that fluting increases the chance of stress redistribution and damage relocation occurring, which in turn increases a point's overall resilience and ability to absorb physical stress, the hypothesis that fluting evolved and spread due to selection should now be considered as well. That does not preclude the possibility that the process of fluting was accorded significance beyond its possible utilitarian value. Indeed, the fact that it was practiced relatively briefly during a particular period in the North American past (and nowhere else), would suggest that its selective advantage was not sufficient to 'fix' its place in the technological repertoire of later groups, for whom it may not have had the meaning it had at this moment in time.

ACKNOWLEDGMENTS

The QUEST Archaeological Research Program at Southern Methodist University, and University of Missouri College of Arts and Sciences through the offices of Michael J. O'Brien, provided funds for purchasing the experimental fluted point specimens. M.I.E. is supported by the Kent State University College of Arts and Sciences, and M.I.E., B.A.S. and B.B. are supported by the National Science Foundation (Award ID: 1649395, 1649406, and 1649409).

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