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HEAT TREATMENT SIGNIFICANTLY INCREASES THE SHARPNESS OF SILCRETE STONE TOOLS*

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Humans were regularly heat-treating stone tool raw materials as early as 130,000 years ago. The late Middle Stone Age (MSA) and Late Stone Age (LSA) of South Africa's Western Cape region provides some of the earliest and most pervasive archaeological evidence for this behaviour. While archaeologists are beginning to understand the flaking implications of raw material heat treatment, its potential functional benefits remain unanswered. Using silcrete from the Western Cape region, we investigate the impact of heat treatment on stone tool cutting performance. We quantify the sharpness of silcrete in its natural, unheated form, before comparing it with silcrete heated in three different conditions. Results show that heat-treated silcrete can be significantly sharper than unheated alternatives, with cutting forces halving and energy requirements reducing by approximately two-thirds. The data suggest that silcrete may have been heat treated during the South African MSA and LSA to increase the sharpness and performance of stone cutting edges. This early example of material engineering has implications for understanding Stone Age populations' technological capabilities, inventiveness and raw material choices. We predict that heat-treatment behaviours in other prehistoric and ethnographic contexts may also be linked to increases in edge sharpness and concerns about functional performance.

KEYWORDS: HEAT TREATMENT, SILCRETE, DURABILITY, CONTROLLED EXPERIMENT, STONE TOOL FUNCTION, THERMAL ALTERATION, EARLY PYROTECHNOLOGY

INTRODUCTION

Archaeologists consider the heating of stone a complex and early example of material engineering (Brown *et al*. 2009; Webb and Domanski 2009). Some even argue that this behaviour is associated with the emergence of so-called 'modern humans' (Marean 2015). Earlier populations engineered their tools by strategically selecting raw materials, by improving technological strategies, or through the extraction and creation of natural adhesives (Braun *et al*. 2009; Eren and Lycett 2012; Hoffecker 2018; Kozowyk and Poulis 2019; Key *et al*. 2020). The heat treatment of stone, however, represents only the second suggested example of a material being intentionally modified to alter its physical properties beneficially (the earliest being the heat treatment of wood; Aranguren *et al*. 2018; Rios-Garaizar *et al*. 2018).

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Prehistoric technologies require motor mechanic and cognitive skills, practice, and socially supported learning that are evidence of behavioural complexity, shedding a light on the behaviour and structure of past groups (Stolarczyk and Schmidt 2018). South Africa displays the earliest evidence for stone heat treatment, with the Middle Stone Age (MSA) sites of Mertenhof, Hollow Rock shelter, Pinnacle Point and Blombos Cave regularly containing heat-treated silcrete from about 72,000 years ago (Kya) (Brown *et al*. 2009; Mourre *et al*. 2010; Schmidt and Högberg 2018). Earlier evidence for thermally altered stone includes the 164 Kya layers at Pinnacle Point (Brown *et al*. 2009), the MIS5e deposits at Hoedjiespunt (Schmidt *et al*. 2020), and MSA deposits at Diepkloof rock shelter on South Africa's west coast. Diepkloof rock shelter shows regular occurrences of heat-treated stone from about 100 to 50 Kya (Porraz *et al*. 2013; Schmidt *et al*. 2013, 2015). The European Upper Palaeolithic, the Neolithic in the Near East, Europe and Asia, along with some American Paleo-Indian assemblages have also yielded evidence of stone heat treatment (Flenniken 1987; Jeske 1989; Delage and Sunseri 2004; Domanski and Webb 2007; Zhou *et al*. 2014; Schmidt and Morala 2018. Thus, from about 130 Kya (Schmidt *et al*., 2020), stone heat treatment became part of some *Homo sapiens*' behavioural repertoire. We hypothesize that such an investment provided groups with benefits significant enough to warrant heat treatment's spread and persistence.

When discussing heat treatments' benefits for stone tool production, most studies mention the increased ability to produce larger and longer flakes using less force (Crabtree and Butler 1964; Mandeville and Flenniken 1974; Bleed and Meier 1980; Schindler *et al*. 1982; Domanski *et al*. 1994) and the capacity to increase the predictability of a rock's fracture properties (Schmidt *et al*. 2019). Although a recent study by Mraz *et al*. (2019), using standardized chert nodules and automated flaking, found no evidence in support of the impact of heat treatment on the morphology of flakes, further validation of this result under real-world knapping conditions is required (in part because their experiment did not control for force). Pargeter and Schmidt (2020) demonstrate that silcrete heat treatment also allows for the production of miniaturized stone implements and facilitates increased core-reduction intensity. Some archaeologists argue that the systematic production and use of small cores and flakes depends on the use of better quality rocks. When these are unavailable, or when they are scarce, humans can engineer suitable rocks through heat treatment (Brown *et al*. 2009; Pargeter and Shea 2019).

Previous research has emphasized that heat treatment may also be linked to different lithic technologies' functional performance. In particular, archaeologists have argued that the sharpness of a tool's cutting edge increases with a stone's heat treatment (Rick and Chappell 1983; Domanski *et al*. 1994; Domanski and Webb 2007; Torchy 2015). Rick and Chappell (1983, 74) provide an early discussion when stating, 'the minimum dimension, or sharpness, of an unaltered edge is the size of the unbroken crystals. In heat-altered material these […] edges have a smaller dimension, and thus greater sharpness'. Torchy's (2015) results supported Rick and Chappell's (1983) prediction, by linking increases in edge regularity at the microscale to reductions in force requirements when cutting with heat-treated flint. Both Rick and Chappell (1983) and Torchy (2015) highlight the link between tip geometry (radius) and edge sharpness that is well supported in engineering sciences (Reilly *et al*. 2004; Atkins 2009; Key 2016).

To date, however, it remains unknown whether stone tools made from heat-treated raw materials *actually* display sharper edges relative to unheated alternatives. Indeed, the hypothesis that prehistoric toolmakers' desire to increase the sharpness, and in turn functional performance, of stone tools drove early forms of thermal engineering (cf. Brown *et al*. 2009) remains untested. Here we redress this gap in our understanding and investigate whether stone tools made from heat-treated raw materials display functional benefits over unheated alternatives. Specifically, we investigate the sharpness of stone tool edges using controlled cutting tests, and quantify how the results vary between heat-treated and unheated silcrete collected from South Africa's Western Cape region.

METHODS

As detailed by Reilly *et al*. (2004), the sharpness of a cutting edge can be defined geometrically by an edge apex's radius, or mechanically by the force, energy (work) and material deformation (displacement) required to perform a cut. These sharpness measures operate independently from the angles observed on a flake tool's cutting edge (Reilly *et al*. 2004; Key 2016). Indeed, while both can impact a tool's performance (Key *et al*. 2018), sharpness (geometrically defined at a microscale by tip radius) and edge angle are two distinct and discreet attributes. It is important to emphasize this point as archaeologists often assume that edge angle *is* edge sharpness, or that the two are one and the same (e.g., Lemorini *et al*. 2015; Zaidner and Grosman 2015; Hardy *et al*. 2018). Controlled cutting tests have validated the suitability of mechanical data to describe sharpness on multiple occasions (McCarthy *et al*. 2010; Schuldt *et al*. 2013, 2018). These definitions and testing methods apply equally to metal and stone cutting edges (Key 2016).

Archaeologists recently introduced mechanical tests of stone tool edge sharpness to Palaeolithic research. Their experiments investigate how sharpness varies between stone edges made from different raw materials (Key *et al*. 2020), how stone cutting edges perform relative to copper alternatives (Bebber *et al*. 2019) and the rate that a stone's edges blunt (Key *et al*. 2018). These studies are part of a broader movement within archaeology to apply mechanical research techniques to answer functional questions (e.g., Key 2016; Milks *et al*. 2016; Bebber 2017; Thomas *et al*. 2017; Kozowyk and Poulis 2019; Schmidt *et al*. 2019; Calandra *et al*. 2020; Key and Lycett 2020; Marreiros *et al*. 2020).

Raw material samples

Here the sharpness of a single raw material, pedogenic silcrete from near Hopefield (South Africa), is investigated after being exposed to three distinct heat-treatment conditions obtained from two heating experiments. The study also included one unheated control sample. This type of silcrete (also termed weathering profile silcrete) is a pedogenic silica rock that forms by concretion of near-surface sediments with a secondary generation of quartz (Summerfield 1983). This leads to a structure including clasts, mostly quartz, sitting in a matrix of finer quartz crystals. Silcrete contains molecular and chemically bound water and up to a few vol% pore-space (Schmidt *et al*. 2017a) that worsens its knapping quality as compared with flint and chert. Most silcretes are also significantly more heterogeneous than finder-grained silica rocks. Therefore, one single silcrete block was broken to produce the four smaller nodules used in the experiments, thus maintaining material consistency among samples. The experiment's two heating conditions are outlined below. Pargeter and Schmidt (2020) describe these heating conditions in greater detail.

Experiment 1: Containing two heat-treatment conditions The first heating condition used a fire made from *Searsia laevigata* wood (as documented at Diepkloof Rock Shelter; cf. Cartwright 2013), building on previous silcrete heat-treatment experiments (Schmidt *et al*. 2015, 2017b). The wood fuel for this experiment was collected on the premises of Diepkloof farm (Western Cape, South Africa) and fresh branches were cut into about 30 cm lengths, keeping the leaves in place.

We heated one silcrete nodule (about 2.1 kg) within the *S. laevigata* ash and embers cone (Fig. 1). P.S. maintained the fire until a cone of embers and ashes formed below the burning branches, before pushing apart the embers and inserting the silcrete nodule at the base of the cone (Schmidt *et al*. 2017b). The embers were then moved to cover the silcrete block so that it sat in the middle of the ash and embers cone (Fig. 1, f).

In the second heating condition we used the same protocol but replaced the fresh *S. laevigata* wood with dry *Acacia erioloba* wood (for a more detailed justification, see Pargeter and Schmidt 2020). We chose *A. erioloba* to recreate the more 'extreme heating conditions' (i.e., higher heating temperatures) used in previous silcrete heat-treatment experiments (Schmidt *et al*. 2015). Again, the silcrete nodule (about 2.4 kg) was heated at the base of the ash and embers cone. For both conditions of experiment 1, the silcrete nodules were left to cool in the ashes overnight, producing an effective heating time of several hours.

Experiment 2: Containing one heat-treatment condition This experiment evaluated the effect of a minimal effort surface heating strategy using fresh *S. laevigata* wood by placing one silcrete nodule onto glowing embers at the base of the fire (Fig. 1, e). This heating strategy corresponds to the simplest perceivable way of heat treating silcrete in an open fire. The silcrete nodule was removed from the embers after 30 min and left to cool.

Figure 1 *Two examples of flakes—unheated (a) and the S. laevigata condition in experiment 1 (b)—secured into wooden blocks. The experimental set-up, including the Instron testing machine, metal frame and upper-grip securing a wooden block, are also depicted (c, d). The heating conditions in experiment 2 (e) and experiment 1 (f) are also shown. Note the silcrete heating on the surface of the fire (e), while the silcrete is buried within the middle of the fire and embers cone (f). [Colour figure can be viewed at wileyonlinelibrary.com]*

Following heat treatment, each silcrete nodule was broken into several sub-nodules to facilitate knapping. We used a freehand strategy where knapping proceeded until accidents (step and hinge fractures, obtuse flake angles) became insurmountable. We used a large canvas to recover all chips, chunks and flakes after knapping. Using a random number generator, we then selected 100 flakes from each knapping session for a separate study of flake quality and flaking efficiency (Pargeter and Schmidt 2020).

J.P. selected 30 silcrete flakes with at least a 15 mm of homogenous (straight, no microfractures) cutting edge from each heat-treatment condition. These flakes were then sent to A.K. for testing, who was kept 'blind' as to each flake's specific heating condition. This effectively controlled against any selection bias for specific flake types. Flake edge angle impacts cutting force requirements during stone tool use and covaries with edge sharpness (Key and Lycett 2015; Key *et al*. 2018). Thus, we attempted to control for edge angle variation at this initial flake-selection stage by selecting flakes with edge angles approaching 30°, measured using the Dibble and Bernard (1980) 'calliper method'. Subsequently, the most homogenous 10 mm length of each cutting edge was identified for use in the controlled cutting test (see the second section). Using the same angle measurement method, a further six measurements were recorded on this 10 mm portion of edge (at depths of 2 and 4 mm away from the edge apex, at distances of 0, 5 and 10 mm). We used the average of these values as each flake's final record of 'edge angle'. When edge angles deviated substantially from 30°, we attempted to replace the flake with another suitable alternative. Table 1 presents the descriptive edge angle data for these four flake assemblages.

Kruskal–Wallis and Mann–Whitney pairwise tests showed significant differences ($p < 0.0001$; $H = 27.221$ and $p = 0.5200$ to < 0.0001, respectively) between the two heat-treatment conditions of experiment 1 and the remaining conditions, despite our efforts to control for edge angle between the four silcrete samples. On average, samples from experiment 1 were 6° more acute than those from experiment 2 and the unheated condition. Anderson–Darling tests ($p = 0.1553$–0.6564, $A = 0.269$–0.5367) revealed three of the four edge angle data sets were normally distributed, with the only exception being the experiment 2 *A. erioloba* flakes

Table 1 *Descriptive edge angle data for flakes in the four heat-treatment conditions. Both the main test (n = 30) and edge-angle-adjusted (n = 20) samples are included*

	Unheated	*Experiment 2*	*Experiment 1:* S. laevigata	*Experiment 1:* A. erioloba
*Main test (*n *= 30)*				
Mean (°)	34.2	32.5	26.1	26.7
SD (°)	7.4	6.5	5.4	7.3
CV (%)	21.5	20.0	20.6	27.4
Maximum (°)	49.1	48.6	40.5	36.7
Minimum (°)	16.6	23.7	16.1	13.8
*Edge-angle-adjusted subsample (*n *= 20)*				
Mean (°)	30.5	28.9	29.0	31.0
SD (°)	5.8	3.3	3.7	4.4
CV (%)	19.1	11.2	12.9	14.3
Maximum (°)	37.3	34.2	40.5	36.7
Minimum (°)	16.6	23.7	22.8	22.6

Note: CV, coefficient of variation; SD, standard deviation.

at the α=0.05 level (p=0.0439, A=0.755). All the data sets were normally distributed after correcting the α-levels using Bonferroni correction (such that α = 0.0125).

Controlled cutting tests

Before use, each flake was secured into a wooden block using polyurethane adhesive. The wooden block secured flakes into the upper grip of the Instron 3345 universal testing machine used to perform the cutting tests (Fig. 1). Each flake was orientated transversely in the block such that its edge was perpendicular to the motion of cutting. The Instron testing machine moves its upper grip in a vertical plane, and records the force (N) and displacement (mm) experienced while doing so. Hence, we could lower the flake cutting edges onto a target material at a known speed until cut is formed.

Our target cutting material was 2 mm thick polyvinyl chloride (PVC) tubing. Previous experiments have demonstrated how this PVC tubing (Key *et al*. 2020) and other similar materials (McCarthy *et al*. 2010; Torchy 2015; Schuldt *et al*. 2016; Key *et al*. 2018; Bebber *et al*. 2019) allow comparable conditions between cutting tests while simultaneously providing a material that allows for deformation before stiffening and fracturing (in a manner similar to biological tissues; Atkins 2009). The PVC tubing was secured onto a steel frame such that it was fully extended (but not stretched) and perpendicular to both the direction of cutting motion and the length of the flake's cutting edge (Fig. 1).

Before cutting tests commenced, the edge of each flake was aligned with the surface of the PVC tubing. Flakes were then moved onto the PVC tube at 20 mm/min (20 Hz) until the PVC stiffened and its edges created a stress enough to fracture (i.e., cut). We define the moment at which the PVC tube separated as the point of 'cut initiation', from which records of force (N) and displacement (mm) were recorded. We calculated the area under each cutting test's force-displacement curve to identify the energy (work in joules, J) required for a cut to form. We did this by visualizing each curve as a series of rectangles defined by the distance between each displacement measurement (usually every 0.01–0.03 mm) on the x-axis and force measurements (N) on the y-axis (Fig. 2). By identifying and combining the work (J) contained within each of these rectangles ($m \times$ N), we were able to calculate the area under each stress–strain curve, and therefore the total work required to cut (with a small margin of error).

Two cutting trials were performed by each flake. The first trial tested flakes in an undamaged, unworn and unused condition (i.e., flakes were 'fresh'). The second cutting trial tested flakes after they had performed five cuts on an oak branch (i.e., flakes were 'used'). We attempted to maintain the angle of application and force levels during these cuts; however, some limited variability is inevitable. Comparison of fresh flakes between all heat-treatment conditions allowed an investigation of the three sharpness metrics (force, work and displacement) when the silcrete edges were sharpest. By comparing used flakes, we could investigate relative sharpness between the different heat-treatment conditions after edges were used and partially blunted. Finally, by comparing force, work and material displacement differences between 'fresh' and 'used' conditions within each heating condition, we tracked edge durability and blunting rates, and tested for differences between heat-treatment conditions.

Statistical analyses

Main analyses We performed four sets of statistical tests using PAST (v. 3.25). Six analysis of covariance (ANCOVA) tests examined sharpness differences between the four silcrete

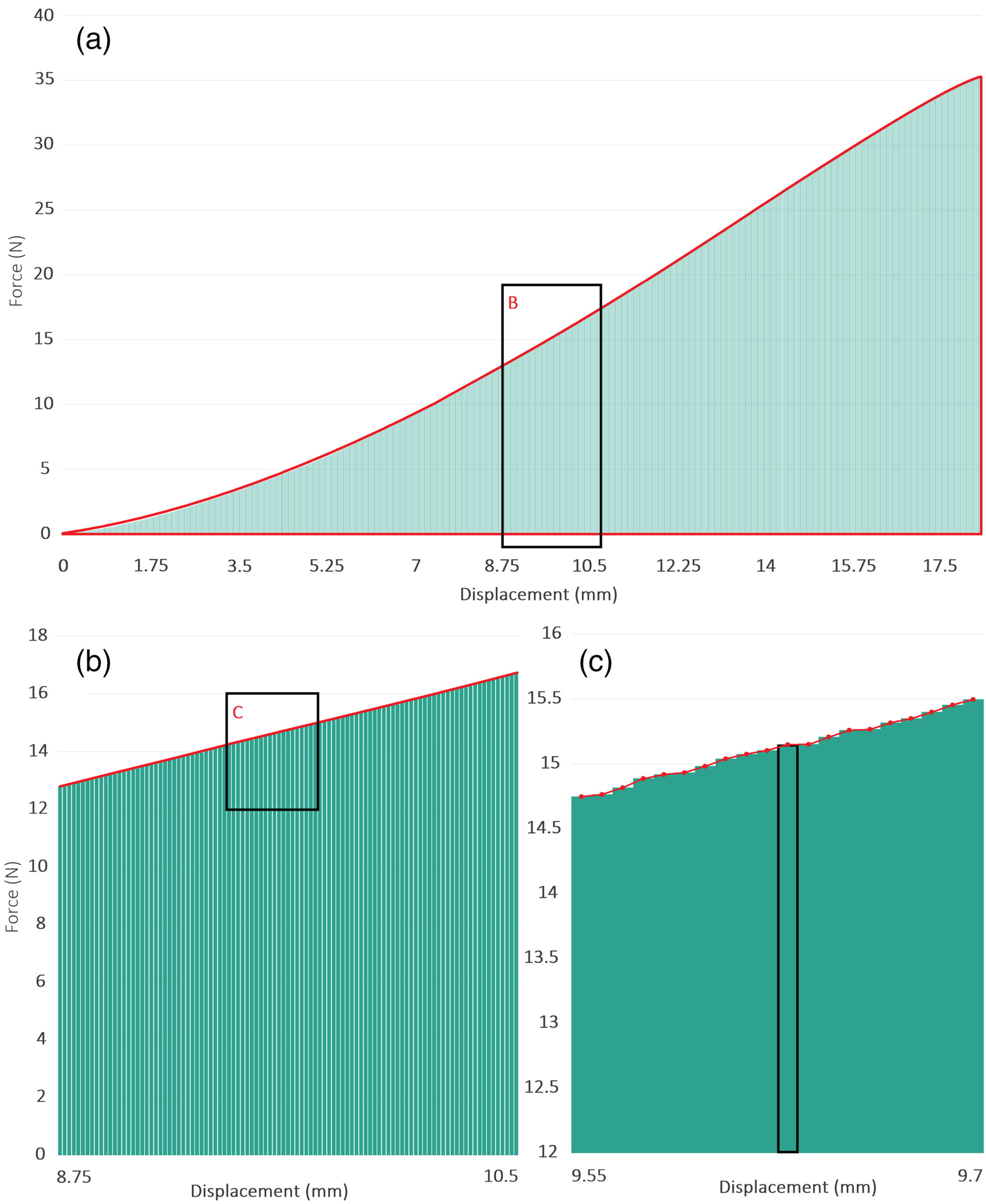

Figure 2 *How work (J) was calculated. We multiplied the distances (m) each flake moved between each data record (20 Hz) by the force (N) recorded at that point (e.g., 0.0003 × 6.755). This was repeated for all data points between a cutting test starting and the point of cut initiation, which, when combined, accounts for the near complete energetic value of the space beneath the stress strain curve. (a) The whole strain–displacement curve, with the total energy used to perform the cut shown. (b, c) Successively smaller portions of the area under the curve, with (c) the top portion of the energy calculated for a single datum point. [Colour figure can be viewed at wileyonlinelibrary.com]*

heat-treatment conditions for both 'fresh' and 'used' flakes. These analyses tested the strength of difference in performance values independently for force, work and material deformation records. ANCOVA tests were run to control for any potential influence of edge angle variation between the samples. In other words, the performance data were adjusted according to, and to account for, any edge angle differences observed between the four sets of flakes (most notably between experiment 1 and the other two conditions). We used the eta squared (η^2) metric to track statistical effect sizes (the magnitude of effect or association between two or more variables).

Post-hoc Tukey HSD tests revealed where significant differences between the four heat-treatment conditions lay. Fresh and used flake data were investigated separately, as were the three performance metrics (force, work and material deformation). We applied a Bonferroni correction to our α-levels to control for Type 1 errors such that α=0.008. We also used linear regressions to identify the strength of the relationship between flake edge angle and force, work, and material deformation in each of the four conditions (after Bonferroni correction, α=0.0125). These models allowed us to investigate further any potential impact of edge angle differences (between flake groups) on flake sharpness.

Finally, we calculated percentage changes in force, work and material deformation to understand better the scale of change in each performance metric between fresh and used conditions and the rate of blunting after five abrasive cutting strokes. Subsequently, Mann–Whitney *U*-tests examined whether the five abrasive cutting strokes distinguishing 'fresh' and 'used' conditions were enough to cause significant reductions in performance within each flake sample, and therefore each heat-treatment condition.

Edge-angle-adjusted subsample analyses Due to the differences in mean edge angle observed between flakes in experiments 2 and 1 and the unheated condition (4–6°), we decided to run a second set of analyses using edge-angle-controlled subsamples of the original 30 flakes. This included completed reiteration of the same battery of tests and analyses with the 'used' flakes (the flakes had already been used, and thus we could not reinvestigate 'fresh' data). We excluded the 10 most obtuse flakes from the unheated and experiment 2 silcrete assemblages, and the

Table 2 *Descriptive data for each heat-treatment condition's force, work and material displacement records during both 'fresh' (F) and 'used' (U) conditions (n=30 in all conditions) of the main test*

		Unheated		*Experiment 2: 30 min*		*Experiment 1:* S. laevigata		*Experiment 1:* A. erioloba	
		F	*U*	*F*	*U*	*F*	*U*	*F*	*U*
Force (N)	Mean	68.2	71.0	66.5	71.3	36.4	48.0	38.6	50.4
	SD	15.4	12.9	14.7	16.1	11.7	12.8	14.7	10.6
	CV (%)	22.6	18.2	22.1	22.6	32.1	26.7	38.1	21.0
Energy (J)	Mean	1.215	1.320	1.057	1.266	0.341	0.562	0.383	0.601
	SD	0.631	0.599	0.518	0.722	0.251	0.325	0.278	0.247
	CV (%)	52.0	45.4	49.0	57.1	73.6	57.7	72.4	41.2
Material displacement (mm)	Mean	36.3	38.1	34.6	36.8	20.4	25.6	22.3	27.7
	SD	8.2	7.9	6.9	8.5	5.4	6.0	5.8	4.6
	CV (%)	22.6	20.7	19.9	23.1	26.3	23.4	25.9	16.8

Note: CV, coefficient of variation; SD, standard deviation.

10 most acute flakes from the experiment 1 assemblages (i.e., n=20). This had the effect of removing any between-group statistical differences in edge angle (Table 1 and see Tables S3–S4 in the additional supporting information).

We used analysis of variance (ANOVA) models to test for sharpness differences between the four silcrete heat-treatment conditions. These three tests focused on the strength of differences in performance values for force, work and material deformation records. Post-hoc Tukey HSD tests revealed where significant differences identified through the ANOVA tests lay.

RESULTS

Main analyses

Table 2 presents descriptive data for each sharpness metric. The data show substantive differences between both of experiment 1's conditions and the remaining two samples (Fig. 3). When flakes are fresh and at their sharpest, samples from experiment 1 require roughly half as much force and about one-third of the energy to cut. These flakes displaced the PVC tube significantly less. These differences are maintained when flakes have been used (although the scale of difference is reduced) and when performance data are adjusted to account for edge angle variation

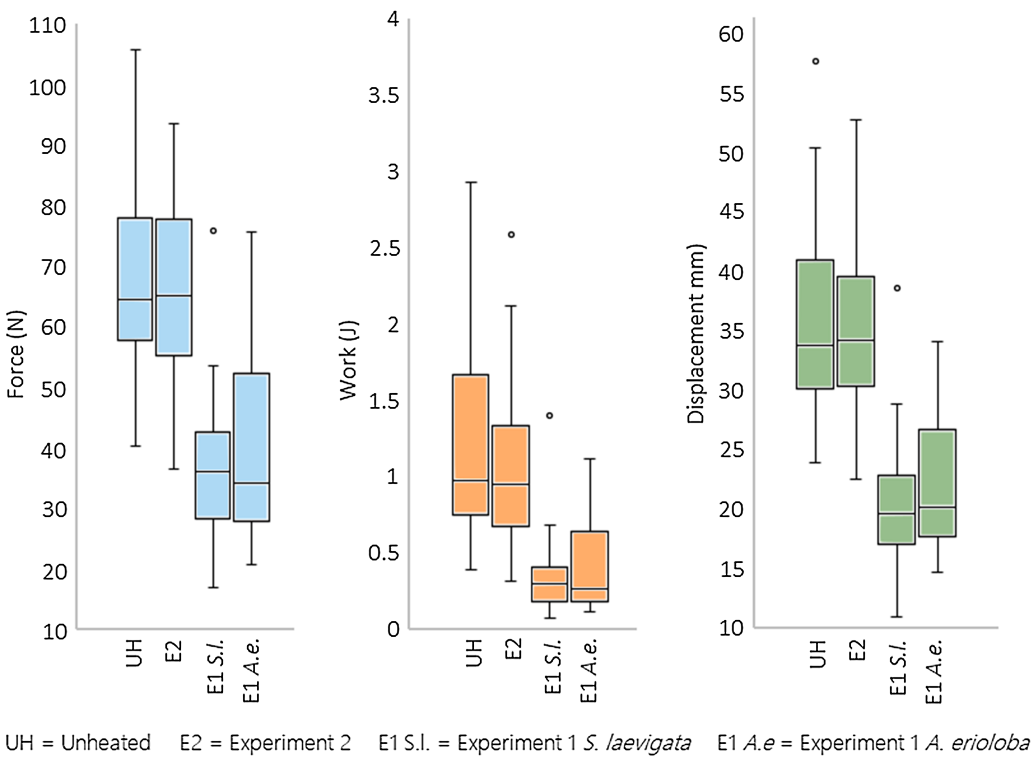

Figure 3 *Box plots highlighting differences in force (N), work (J) and material displacement (mm) between the four heat-treatment conditions during the first set of cutting tests (i.e., using 'fresh' flakes). For a version of this figure that includes both used and fresh flakes, see Figure S1 in the additional supporting information. [Colour figure can be viewed at wileyonlinelibrary.com]*

(Table 2 and see Table S1 in the additional supporting information). Coefficient of variations (CVs) are higher in experiment 1's two conditions, suggesting greater variation in edge micro-morphology after heat treatment. There are few differences between the unheated silcrete flakes and those made from nodules heated in experiment 2.

The results of the ANCOVA tests confirm that even when force, work and displacement data are adjusted according to any influence exerted by edge angle variation, significant performance differences still exist between heat-treatment conditions. These differences are observed in fresh and used flakes (Table 3). The post-hoc Tukey HSD tests identify that, in all instances, across both fresh and used flakes, the results mirror the descriptive data (Table 4 and see Table S2 in the additional supporting information). In every instance, the first experiment 2 conditions display significantly lower performance values, and therefore significantly sharper edges, compared with the other two conditions. No significant differences are observed between the unheated flakes and those heated in experiment 2.

Linear regression between edge angle and sharpness within each silcrete sample reveal positive relationships (Table 5), suggesting some performance variation is related to this macroscopic edge form attribute. Importantly, however, R^2-values are low to moderate (0.02–0.23) and there

Table 3 *Results from the six analysis of covariance (ANCOVA) tests where data are compared after adjustment for edge angle differences between flake groups (α = 0.05)*

	Force			*Work*			*Material displacement*		
	p	*F*	η^2	*p*	*F*	η^2	*p*	*F*	η^2
Fresh	< 0.0001	26.47	0.408	< 0.0001	27.91	0.421	< 0.0001	17.77	0.317
Used	< 0.0001	16.98	0.307	< 0.0001	14.98	0.281	< 0.0001	10.89	0.221

Note: Effect sizes (eta squared [η^2]) are moderate to large in all instances.

Table 4 *Tukey HSD tests between the four heat-treatment conditions for each sharpness performance metrics used*

	Experiment 2	*Experiment 1:* S. laevigata	*Experiment 1:* A. erioloba
Force			
Unheated	0.9694	< **0.0001**	< **0.0001**
Experiment 2		< **0.0001**	< **0.0001**
Experiment 1 *S. laevigata*			0.9356
Work			
Unheated	0.5237	< **0.0001**	< **0.0001**
Experiment 2		< **0.0001**	< **0.0001**
Experiment 1: *S. laevigata*			0.9830
Material displacement			
Unheated	0.7595	< **0.0001**	< **0.0001**
Experiment 2		< **0.0001**	< **0.0001**
Experiment 1: *S. laevigata*			0.7008

Note: Data relate to flakes in the 'fresh' condition (α = 0.005).

Table 5 *Linear regressions between force (N), deformation (mm) and work (J) at cut initiation and flake edge angle (°) across all four heating conditions (n = 30 in all instances)*

	Force		*Material deformation*		*Work*	
	p	R^2	*p*	R^2	*p*	R^2
Unheated	0.1821	0.063	0.4624	0.019	0.4433	0.021
Experiment 2	**0.0073**	0.230	**0.0110**	0.210	**0.0367**	0.147
Experiment 1: *S. laevigata*	**0.0193**	0.180	**0.0108**	0.210	**0.0236**	0.170
Experiment 1: *A. erioloba*	0.1346	0.078	0.1840	0.062	0.1851	0.062

Note: All results display positive relationships between edge angle and flake sharpness. For two heating conditions, these relationships were significant, with 15–23% of sharpness variation explained by edge angle.

are no consistent differences between experiment 1 and the other two samples. Further, regression equations for the first experiment's two conditions, once adjusted for a 6° increase in mean edge angle (i.e., the independent variable), predict mean sharpnesses substantially below those observed in experiment 2 and the unheated data sets. For example, experiment 1's *S. laevigata* condition displays the strongest relationship with edge angle (Table 5), yet its predicted mean force after adjustment for the 6° edge angle difference is only 42 N ((i.e., 12.312 + (32.1 × 0.927) = 42.054). That adjusted result is about 24 N lower than the unheated and experiment 2 flakes. The relatively small edge angle differences observed between flake samples therefore do not account for the magnitude of sharpness differences we identify. Heat treatment is responsible for these flake sharpness differences.

Table 6 details the levels of change observed between fresh and used flakes for each heating condition expressed as a percentage. Again, there are substantive differences between the first experiment's two conditions and the other two samples. Both of experiment 1's conditions display changes of about 14%, about 18% and about 30% for displacement, force and work measures, respectively. The other two samples display lower percentage changes of around 3–7% across sharpness metrics.

Table 6 *Levels of change expressed as a percentage between the fresh (F) and used (U) flakes for each sharpness metric and heat-treatment condition*

	Mean % increase		
	Force F ↔ U	*Work* F ↔ U	*Material displacement* F ↔ U
Unheated	3.0	5.8	3.2
Experiment 2 30 min	4.0	7.4	3.2
Experiment 1: *S. laevigata*	17.6	30.4	14.5
Experiment 1: *A. erioloba*	17.9	29.2	14.2

Mann–Whitney *U*-tests show that these differences are significant for both experiment 1's conditions (Table 7). That is, force, work and displacement significantly increased between the fresh and used edges. Five cuts on an oak branch were not, however, enough to significantly decrease edge sharpness (and therefore significantly increase blunting) for the unheated silcrete or the flakes heated in experiment 2 (Table 7).

Edge-angle-adjusted subsample analyses

Results obtained with controlled subsamples were nearly identical to those obtained in the main analyses (Tables 8–10). That is, the ANOVA tests identified significant differences in each sharpness metric between the four heat-treatment conditions (Table 9). Tukey HSD tests showed flakes in experiment 1 to have significantly sharper edges compared with those in experiment 2, or the unheated condition (Table 10). The only difference in these adjusted samples was a sharpness increase in experiment 2 relative to the unheated flakes, although this difference was not significant (Table 10).

DISCUSSION

The heat treatment of stone is a behaviour that, thus far, appears unique to *H. sapiens* and was practiced widely from about 130 Kya onwards (Brown *et al*. 2009; Schmidt *et al*. 2020). Archaeologists hypothesize that prehistoric toolmakers practiced heat treatment because it lowered the fracture toughness of stone while increasing its fracture predictability (changes in the Weibull modulus) and hardness. Researchers have further hypothesized that these changes improve the 'knappability' of certain stone types because the predictability of flaking increases as the forces required for flake detachment decrease (Bleed and Meier 1980; Domanski *et al*. 1994, 2009; Mraz *et al*. 2019; Schmidt *et al*. 2019).

Previous works also propose utilitarian advantages to the tools produced from heat-treated stone, including increases in the sharpness of their edges (Rick and Chappell 1983; Domanski *et al*. 1994; Domanski and Webb 2007). Before the present study, however, the functional implications of producing stone tools from heat-treated raw materials, and any benefits in terms of edge sharpness, remained largely untested (although see Torchy 2015). Using controlled experiments and mechanically defined performance characteristics (cf. Schiffer and Skibo 1997), we demonstrate that heat treatment significantly increases the sharpness of silcrete stone tools.

Table 7 *Results of Mann–Whitney U-tests examining force (N), work (J) and displacement (mm) differences between the fresh (F) and used (U) flakes within each heat-treatment condition*

	Mann–Whitney U-*test*		
	Force $F \leftrightarrow U$	*Work* $F \leftrightarrow U$	*Material displacement* $F \leftrightarrow U$
Unheated	0.3255	0.3401	0.3556
Experiment 2: 30 min	0.2340	0.2675	0.2282
Experiment 1: *S. laevigata*	**0.0003**	**0.0004**	**0.0004**
Experiment 1: *A. erioloba*	**0.0003**	**0.0004**	**0.0003**

Table 8 *Descriptive data for each heat-treatment condition's force, work and material displacement records in the retested edge-angle-subsampled flakes (n = 20 in all conditions)*

		Unheated	*Experiment 2*	*Experiment 1:* S. laevigata	*Experiment 1:* A. erioloba
Force (N)	Mean	70.4	64.5	48.8	47.1
	SD	13.3	13.9	14.5	9.1
	CV (%)	19.0	21.5	29.8	19.4
Energy (J)	Mean	1.259	1.005	0.564	0.526
	SD	0.506	0.421	0.352	0.197
	CV (%)	40.2	41.9	62.5	37.5
Material displacement (mm)	Mean	38.0	33.2	26.0	26.5
	SD	7.5	6.2	6.8	3.7
	CV (%)	19.8	18.6	26.1	13.8

Note: CV, coefficient of variation; SD, standard deviation.

Table 9 *Results from the three analysis of variance (ANOVA) tests between sharpness performance metrics for the four edge-angle-adjusted subsampled (n = 20) flake groups (α = 0.05)*

	ANOVA		
	Force	*Work*	*Material displacement*
p	< 0.0001	< 0.0001	< 0.0001
F	16.01	16.84	17.2

Note: The data reveal there to be significant differences in each sharpness metric between the four silcrete flake groups.

Table 10 *Tukey HSD tests between the four heat-treatment conditions for each sharpness performance metric used*

	Experiment 2	*Experiment 1:* S. laevigata	*Experiment 1:* A. erioloba
Force			
Unheated	0.4866	< **0.0001**	< **0.0001**
Experiment 2		**0.0013**	**0.0003**
Experiment 1: *S. laevigata*			0.9764
Work			
Unheated	0.1694	< **0.0001**	< **0.0001**
Experiment 2		**0.0030**	**0.0011**
Experiment 1: *S. laevigata*			0.9898
Material displacement			
Unheated	0.0776	< **0.0001**	< **0.0001**
Experiment 2		**0.0024**	**0.0005**
Experiment 1: *S. laevigata*			0.9937

Note: The tests were run with data from the edge-angle-subsampled flakes (*n* = 20) and they mirror the main test results.

Edge sharpness

Silcrete heated in the middle of a fire's ash and embers cone (experiment 1) displayed significantly sharper edges relative to unheated alternatives, with cutting force requirements reducing by half and energy use decreasing by roughly two-thirds.

It is reasonable to hypothesize that Stone Age populations would have actively sought reductions in energy and force expenditure during stone tool use (Torrence 1989; Kuhn 1994; Bird and O'Connell 2006; Stevens and McElreath 2015). Individuals concerned with such factors in the southern African MSA would therefore have benefited from the use of heat-treated silcrete. Indeed, energy requirements would have decreased considerably, potentially outweighing the costs associated with making and maintaining a fire given that multiple nodules (capable of producing numerous tools) could be heated simultaneously. When the necessity of fire for heating, cooking and safety are also considered, there was likely little energetic cost to engineering stone in this way, but (and as demonstrated here) substantial benefit. Further, 'ease-of-use' perceptions linked to working-force requirements would have increased noticeably through stone heat treatment, providing easy and immediate perceivable feedback to tool users. Together, these selective pressures could have provided a strong mechanism favouring the widespread use of heat-treated stone. It would be interesting if future research repeated these investigations using alternative raw material types (e.g., chert; Mraz *et al*. 2019) (Fig. 4).

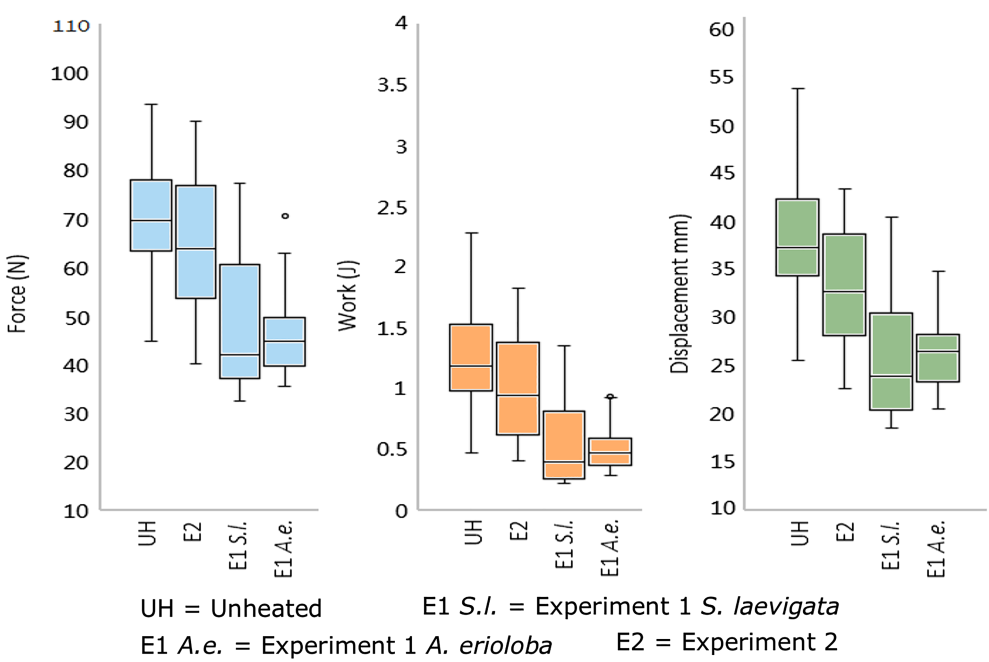

Figure 4 *Box plots highlighting differences in force (N), work (J) and material displacement (mm) between the four heat-treatment conditions during the second set of cutting tests (i.e., using 20 'used' flakes). [Colour figure can be viewed at wileyonlinelibrary.com]*

Edge durability and tip radius comparisons

Silcrete flakes heated in experiment 1 displayed significant sharpness reductions between 'fresh' edges and those tested after having cut a piece of wood five times. In comparison, flakes from the unheated silcrete nodule returned marginal, non-significant, reductions in performance. Percentage changes in sharpness mirrored this difference. We are tempted to conclude that heated silcrete is less durable than unheated silcrete. Certainly, in the very earliest stages of use, unheated flakes appear more durable. Our ability to discern durability in this experiment is, however, hampered by the increased sharpness observed on the edges of heated flakes and the limited number of cutting stokes investigated. That is, because heat treatment increased edge sharpness, the starting point of any durability comparisons were not the same between samples. Future studies comparing larger cutting stroke samples might show that unheated silcrete flakes perform better in more robust tasks (i.e., chopping or sawing wood) compared with heated silcrete flakes.

Heated silcrete likely displays an initially smaller tip-radius (Reilly *et al*. 2004), and therefore smaller tip-offset (Key 2016), compared with unheated edges (Fig. 5). This means that heated silcrete edges have a finer edge profile that, through use, can be more easily abraded in the initial stages of a tool's use, resulting in the significant decreases in cutting performance observed here.

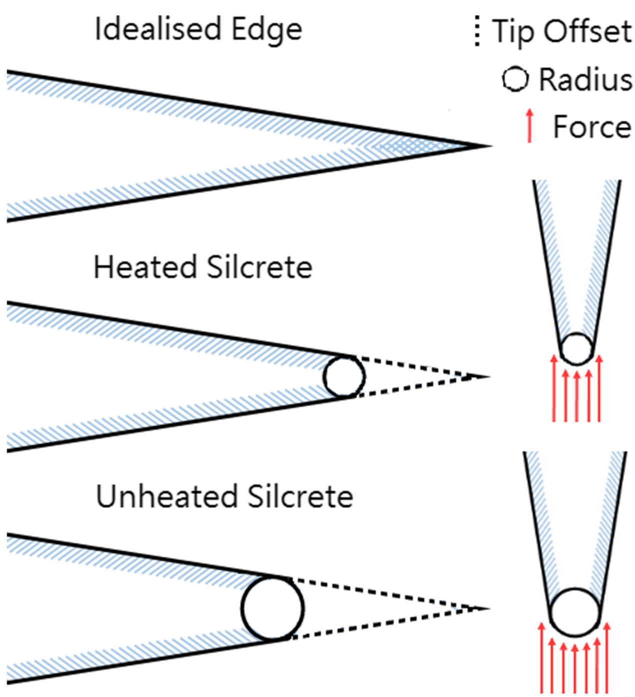

Figure 5 *Simple schematic depiction of three theoretical edge cross-sections. The 'idealized edge' illustrates an edge apex at the upper limit of sharpness when defined geometrically (i.e., the radius is as small as is theoretically possible). The heated and unheated silcrete edges represent the common geometry of stone tool cutting edges, where rounding at the apex is present at the microscale. The unheated silcrete investigated here likely displays a greater tip radius relative to its heated counterpart due to a larger crystalline structure at the edge's tip (Rick and Chappell 1983; Torchy 2015). In turn, and as illustrated on the right, unheated silcrete would experience greater resistance, and require greater forces, during cutting due to its greater surface area at the primary point of contact with a worked material. [Colour figure can be viewed at wileyonlinelibrary.com]*

The blunter but more robust edges seen on the unheated edges would have naturally been more durable, resulting in marginal performance reductions through use. These differences are the result of tip morphology differences and not those related to the material properties of heated and unheated silcrete. Microscopic three-dimensional analyses of edge tip morphology (e.g., Stemp *et al*. 2019) are required to confirm these geometric differences. We cannot attest to how this relationship changes over longer periods, and despite unheated samples initially appearing more durable, the heat-treated silcrete may be more durable in the longer term. Our data, however, reveal that even after an initial period of use, heated silcrete edges are still sharper than 'fresh' unheated alternatives, with lower force, material displacement and energy use requirements (Table 2 and see Fig. S1 in the additional supporting information). At a point heated edges could abrade to a tip geometry that matches the 'fresh' edges observed on the unheated flakes, at which point their sharpness would match and durability could be fairly assessed from this point.

Differences between heat-treatment methods

The data demonstrate that different heat-treatment methods vary in their ability to alter the sharpness of silcrete cutting edges. We find a clear distinction between experiment 1 (embers cone) and experiment 2 ('simpler' core on embers), where only the former method significantly altered the sharpness of flake cutting edges. Similarly, we note a distinction between the two experimental conditions' durability data. Our comparison of differences in the three sharpness metrics show that cutting forces were lower by about 50% and energy requirements reduced by roughly 60% after heat treatment in experiment 1. The heating method employed in experiment 2 (a nodule placed on glowing embers at the base of the fire) resulted in marginal performance increases relative to unheated silcrete (this is more noticeable in the retested subsampled flake data), but these differences were not significant using our data set and statistical testing protocol. Clearly, some heat-treatment methods do not substantially alter the sharpness or cutting performance of silcrete cutting edges as much as others. These results differ to Pargeter and Schmidt's (2020) observations, where heating silcrete using different surface fire techniques had strong practical effects on the flaking outcomes. Both the embers-cone and core-on-embers conditions showed statistically distinct flake cutting edge angles and core utility patterns. This demonstrates that prehistoric toolmakers may have selected for different heat-treatment options based on not only flake performance but also a broader suite of considerations including the ease of flaking, the efficiency of each core's reduction or on learnt cultural biases.

One potential difference between the three heat-treatment conditions was the temperature each nodule was exposed to (Pargeter and Schmidt 2020). The ash and embers cone's temperatures (experiment 1) were evidently required for the physical changes necessary to increase edge sharpness. The simplest possible method for heat treating silcrete (Pargeter and Schmidt 2020) does not, therefore, result in significantly sharper cutting edges. Nonetheless, placing a nodule in the centre of burning embers is still a straightforward technique through which to engineer silcrete as a stone tool raw material.

Presented here is an initial contribution to the study of raw material heat treatment and its functional consequences. When making inferences about factors driving prehistoric technological change, archaeologists traditionally rely on abstract models (i.e., Mesoudi 2008; Premo and Scholnick 2011; d'Errico and Banks 2013) or ethnographic analogies of non-stone tool using groups (i.e., Shott 1986; Kuhn 1994; Mackay *et al*. 2014). While these methods have been widely successful, they require several layers of inference about the costs and benefits of different lithic technological strategies, potentially obscuring the reasons humans chose between different technologies. Experiments such as ours help to build better models for technological change, grounding observations in different sets of middle-range data, and providing possible baseline measures for more abstract methods and alternatives to the ethnographic record.

CONCLUSIONS

This study is the first to demonstrate that heat treatment significantly increases the sharpness of silcrete stone tools. Indeed, when used for cutting purposes there are clear functional advantages to using edges made from thermally altered silcrete (approximately half as much force and one-third of the energy is required to initiate a cut relative to unheated alternatives). This would have provided strong selective pressure for prehistoric toolmakers to engineer their stone tools through raw material heat treatment. We hypothesize that populations realized these benefits and chose to retain and transmit heat-treatment strategies widely in the southern African MSA and LSA. Functional considerations may also be an important factor behind the heat treatment of stone elsewhere in the archaeological record. Our results speak to larger questions about the invention and transmission of Palaeolithic technological innovations.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Mean and adjusted mean sharpness data, as per the analysis of covariance (ANCOVA) analyses. Both fresh and used flake data for each heat-treatment condition are displayed.
Table S2. Tukey HSD tests between the four heat-treatment conditions for each sharpness performance metric used. Data relate to flakes in the 'used' condition (α=0.005). For the 'fresh' condition, see Table 4.
Table S3. To control for edge angle differences between the four silcrete samples, the most obtuse 10 flakes from the unheated and experiment 2 conditions were removed from the analyses, as were the 10 most acute flakes from the experiment 1 conditions. All tests were rerun with data collected from these smaller 20-flake samples (in a used condition). Presented are the results of Kruskal–Wallis and Mann–Whitney pairwise tests between these smaller edge angle data sets (n=20), revealing there to be no significant differences between the flake groups median edge angles (mean edge angles ranged from 29 to 31°).
Table S4. Tests of a normal distribution in the subsample (n=20) of edge-angle-controlled data sets via Anderson–Darling tests. All flakes display normally distributed edge angle data (α= 0.05).
Figure S1. Box plots highlighting differences in force (N), work (J) and material deformation (mm) between the four heat-treatment conditions during both the 'fresh' and 'used' cutting tests (n=30). UH, unheated; E2, experiment 2; E1: *S.l.*, experiment 1: *Searsia laevigata*; and E1 *A.e.*, experiment 1: *Acacia erioloba*.

