



3D multiscale curvature analysis of tool edges as an indicator of cereal harvesting intensity

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ARTICLE INFO

Keywords:

Harvesting tools
Microliths
Focus variation microscopy
Surface metrology
Edge angle measurements
Areal edge curvature

ABSTRACT

The adoption of an agricultural lifeway is considered one of the most significant cultural events in prehistory. Microwear analysis of stone harvesting tools is among the many approaches used to document the transition to agriculture in the Near East. Traditionally, these microwear analyses rely on the use of optical microscopy and visual-verbal descriptions of wear criteria. In addition to traditional optical microscopy, ongoing research into the applications of surface metrology for the characterization of microwear traces has contributed to the development of quantitative microwear methods. Despite significant research into the quantification of lithic microwear polishes, there has been comparatively little research on the quantification of tool edge angles to understand function. In this paper, we test a new method for the quantification of areal curvature of stone harvesting tool edges at multiple scales using data collected with focus variation microscopy. These calculations are based on curvature tensors of the measured surface topographies along tool edge cross sections. This method allows calculation of maximal and minimal curvatures at each location and scale. For this paper, we analyze a set of experimental microliths used as cereal harvesting tools using changes in multiscale areal edge curvature to mathematically document harvesting intensity (duration of use). This experimental research presents a new method for documenting used stone tool edges that will contribute to our understanding of how harvesting tools were used, curated, and discarded in the past, giving insight into the food collection practices of early farmers.

1. Introduction

The origins of agriculture remain one of the most enigmatic developments of prehistory. Understanding why our ancestors transitioned from hunting and gathering to settled communities of farmers and pastoralists continues to spark archaeological debate and inquiry. One avenue to better understand this transition includes investigating how people interacted with flora in their environments and how this relationship changed over time. Lithic functional analysis offers a window within which inferences about human/plant interactions can be framed. Functional analysis, or microwear analysis, uses a range of microscopy types to identify fractures, polishes, striations, and edge rounding on tools to infer how they were used in the past. Although there has been extensive research into the distinctive polishes and striations produced on stone tool surfaces by cereal harvesting, there has been significantly less research characterizing the region of intersection of the dorsal and ventral faces (i.e., edge rounding or edge angles) of stone tools. In an effort to better describe and quantify wear development across the

edges of stone tools, this research explores the application of surface metrology, specifically using focus variation microscopy and a novel multiscale calculation of edge curvature in three-dimensions, to experimental chert harvesting tools to test the method's utility for future archaeological studies of the duration of tool use. Replicated Epipalaeolithic microliths were used for harvesting experiments, recreating a scenario in which late-stage hunter-gatherers were beginning to more intensively use cereals in the local environment. The calculation of the principal maximal (κ_1) and minimal (κ_2) curvatures at different locations and at different scales along the edges of these experimental microliths demonstrated that: 1) the calculated edge curvatures on tools used for different durations were not the same, 2) maximal edge curvature proved more reliable than minimal edge curvature for documenting stone tool edges, and 3) maximal edge curvature on stone tool edges increased with increased duration of use. This was observed at scales between 16.125 and 25.155 and 1.806 and 6.966 μm , depending on magnification. The results of this study demonstrate how multiscale quantification of stone tool edges, and

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<https://doi.org/10.1016/j.jasrep.2020.102523>

Received 25 March 2020; Received in revised form 27 June 2020; Accepted 24 July 2020

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concomitant edge rounding, can provide further lines of evidence for how harvesting tools were used in prehistory and may potentially provide a reliable measure of microlith use-life based on wear development.

2. Background

2.1. Epipalaeolithic harvesting tools

Archaeologists divide Epipalaeolithic (EP) hunter-gatherers in Southwest Asia (21,000–11,500 cal BP) into three different phases: Early, Middle, and Late. Each phase is further subdivided into cultural entities based on lithic technology, often based on the associated microlith types and frequencies found within a site (see [Fellner, 1995](#), [Goring-Morris, 1996](#), [Kaufman, 1995](#), [Neeley and Barton, 1994](#), [Olszewski, 2001](#), [Olszewski, 2006](#), [Olszewski, 2011](#) for discussions and debates). By the early Neolithic there is clear evidence of harvesting activities, however much debate has focused on whether these activities were started by earlier hunter-gatherers in the Late Epipalaeolithic. The Late Epipalaeolithic (Natufian culture) was long seen as a precursor to the following Neolithic period, demonstrating nascent cultural patterns common to later periods such as burials with symbolic grave goods, stone structures, sedentism, and incipient domestication (e.g. [Bar-Yosef, 1998](#), [Bar-Yosef and Belfer-Cohen, 1991](#), [Belfer-Cohen, 1995](#), [Byrd, 2005](#), [Grosman et al., 2008](#), [Nadel et al., 2013](#), [Valla and Bar-Yosef, 2013](#)). Although the interpretation that the Natufian shepherds in the cultural practices seen in the Neolithic has been criticised (e.g. [Maher et al., 2012](#)), it is during this Natufian period that we begin to see increasingly intensive interactions with cereal crops, leading to the origins of agriculture.

Several lithic use-wear studies have been conducted on Southwest Asian Natufian assemblages to identify traces of early harvesting. These studies have shown that microliths (lunates) used during the Natufian were hafted and used for a wide variety of different tasks including as projectile inserts ([Anderson, 1983](#), [Büller, 1983](#), [Marder et al., 2006](#), [Valla et al., 1991](#)), cutting soft materials (meat/hide) ([Richter, 2007](#)), and as insets for cereal harvesting tools ([Anderson, 1991](#), [Anderson and Valla, 1996](#), [Unger-Hamilton, 1989](#), [Unger-Hamilton, 1991](#), [Yamada, 2000](#)). Microliths with diagnostic sickle gloss have been found at Natufian sites such as Kebara, Hayonim Terrace, Nahal Oren, and Jericho ([Anderson, 1991](#), [Anderson and Valla, 1996](#), [Unger-Hamilton, 1989](#), [Unger-Hamilton, 1991](#), [Yamada, 2000](#)), suggesting that they were regularly used as harvesting tools during this period.

Although there is clear evidence indicating that Natufian microliths functioned in part as insets for harvesting implements, how these harvesting tools were used and the nature of cultivation has been subject to much debate. [Unger-Hamilton \(1989, 1991\)](#) analyzed a series of Early and Late Natufian sites to assess the use of harvesting tools during these periods. The results of her study suggested that of the 360 Natufian lithics analyzed, 138 had definitive cereal polish and 182 had probable cereal polish. The majority of the polishes were created through contact with barley or emmer wheat; however, other plants were also harvested, including reeds and bull rushes. Unger-Hamilton also suggested that the presence of striations in the cereal polish on the Natufian tools was indicative of soil tilling, indicating that Natufian people were cultivating cereals. However, this interpretation is highly debated and [Anderson \(1991\)](#) suggests that heavy striations are the result of harvesting close to the ground rather than soil tillage.

Other research by [Yamada \(2000\)](#) into the development of agricultural practices in the Southern Levant from the Late Natufian through the Pottery Neolithic examined changes in harvesting practices based on use-wear traces. He analyzed assemblages from three Natufian sites; Saflulim in the Negev, and Halizon Tachtit and Iraq el-Dubb in the Mediterranean zone, all of which had some evidence of plant harvesting traces, although in small numbers.

Use-wear studies on the Syrian Natufian assemblages from

Mureybet and Abu Hureyra show that geometric microliths functioned primarily as projectile insets ([Anderson, 1983](#)). However, in addition to the evidence for projectile function, there was also some evidence from Abu Hureyra that microliths functioned as insets for sickles ([Anderson, 1991](#)). A sample of eight tools from the site had visible gloss, including five microliths. This gloss was similar to the polish produced from einkorn harvesting experiments leading the author to suggest that the gloss on the archaeological tools was from wheat harvesting. The results of the analysis suggested that cereals were harvested in a green-semi green state and were cut close to the ground, similar to the plant harvesting tools found at Hayonim. Later analysis also suggested that there were some harvesting activities at Mureybet ([Ibáñez, 2008](#)). Subsequent analysis of the harvesting tools from Mureybet and Abu Hureyra used confocal microscopy to characterize surface texture differences between polishes made through wild/semi-ripe wheat versus domesticated/ripe crops ([Ibáñez et al., 2016](#), [Ibáñez et al., 2014](#)). This confocal research expanded to also include analysis of Late Natufian artifacts from Hayonim Terrace ([Ibáñez et al., 2016](#)).

Although not specifically related to microwear analysis, but related to microlith edges, a recent study by [Valletta et al. \(2020\)](#) presents a new technique to measure edge angle on stone tools based on digital 3-D models. These models calculate edge angle based on the complete shape of the tool edge rather than on individual, discrete cross-sectional measurements. Preliminary results based on the application of this technique to assemblages of non-geometric and geometric microliths from seven Epipalaeolithic sites in Southwest Asia suggest that the mean edge angles of the microliths, in combination with maximum tool thickness, indicate certain technological traditions within lithic assemblages. These traditions lasted over long periods of time and had widespread distribution throughout the region. This technique could be coupled with microwear analyses in the future to determine relationships between microlith use, specifically in terms of cereal grass harvesting. However, [Valletta et al. \(2020: 15\)](#) did not note any correlations between edge angle, tool thickness, and intended function in their Epipalaeolithic microlith assemblages.

A few studies have worked towards the quantification of use duration on harvesting tools. These include [Goodale et al. \(2010\)](#) who used scanning electron microscopy to measure the edge thickness on experimental and archaeological tools from the early Neolithic site of 'Dhara to infer the intensity of tool use. The results of this study suggested that as a stone tool was used for harvesting the edge increasingly blunted, with a thicker edge indicating more intensive harvesting. As well, [Vardi et al. \(2010\)](#) attempted to quantify the intensity of sickle use by measuring the brightness of polish using a 'Laser He-Ne' method. Finally, [Linton et al. \(2016\)](#) measured the invasiveness of polish on harvesting tools, suggesting that tools used for longer durations had more invasive polish. Although these studies work towards the quantification of cereal harvesting intensity, they are unable to quantify the shape of the tool's edge in three-dimensions. In this study, we present a new method to measure multiscalar edge curvature in 3D, building on these past studies to allow for more robust methods of edge quantification.

2.2. Stone tool edges and function

Stone tool edge angle has been repeatedly assessed in terms of its importance for tool function; however, some archaeologists ignored stone tool edges in their classification systems (e.g. [Bordes, 1961](#)). Early explorations of the importance of edge angle focused on changes in their sizes and/or shapes, particularly with regard to tool design and the progression of tool use as related to function ([Keller, 1966](#), [Sonnenfeld, 1962](#)). One constant recognized by archaeologists is the increase in stone tool edge angle with increased amounts/lengths of tool use and tool resharpening ([Dibble, 1995: 329](#), [Wilmsen, 1968: 160](#)). When it comes to relationships between tool edge angle and tool function, [Wilmsen \(1968\)](#) is frequently cited as an early contributor to

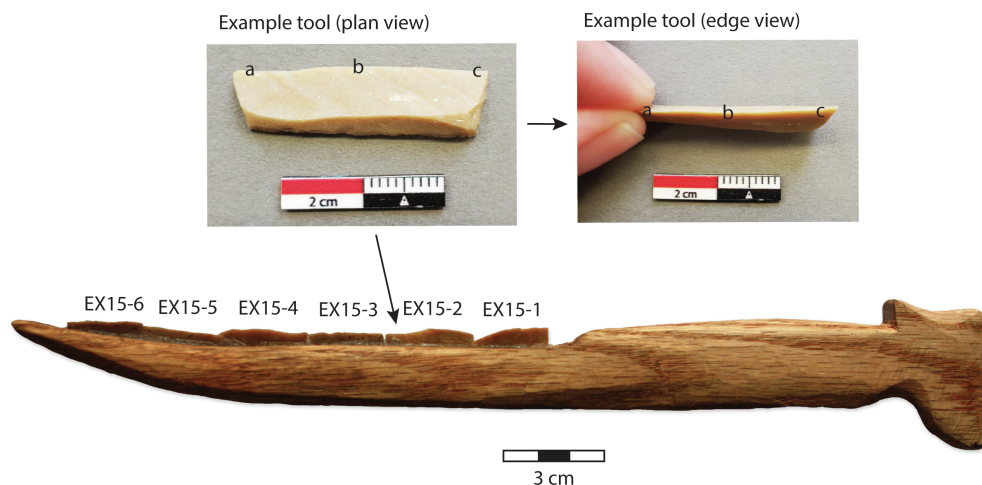


Fig. 1. Harvesting tool (EX-15) with inset microliths. Upper images show scan sampling locations on individual microliths.

subsequent discussions on the topic. Specifically, Wilmsen (1968) discussed the connection between acute edge angles and activities accomplished through longitudinal motions, such as cutting or sawing, and the association of more obtuse edge angles with transverse motion activities, such as scraping, or the working of harder materials. Although the edge angle/function relationship has been variously demonstrated in lithic use-wear studies, it is by no means completely predictive or universally reliable (Lewenstein, 1991, Odell, 1981, Stemp, n.d.). Moreover, research among indigenous peoples in Australia, Ethiopia, and New Guinea has demonstrated that tool edge angle is only one of a number of factors, including tool size, tool shape, tool ergonomics, and stone tool/raw material availability, that affect the choice of a tool for task completion, and that tool sizes and shapes change with resharpening (Gould et al., 1971, Hayden, 1977, Hayden, 1979, White, 1967, White and Thomas, 1972). The importance of considering these other factors, notably grip, pressure, and ergonomics, has also been explored through modern experimentation (e.g. Key, 2016, Key and Lycett, 2015, Key et al., 2016).

In analyses of stone tool function, edge angles are often among the critical variables recorded when conducting use-wear analysis (e.g. Borel et al., 2013, Broadbent and Knutsson, 1975, Collins, 2008, Eren, 2013, Eren and Lycett, 2016, Hurcombe, 1992, Iovita et al., 2014, Jensen, 1986, Jones, 1980, Keeley, 1980, Key et al., 2018, Key and Lycett, 2015, Key et al., 2016, McCall, 2005, Schousboe, 1977, Siegel, 1985, Tringham et al., 1974, Vaughan, 1981, Vaughan, 1985). Although this makes sense given observations discussed above, edge angles are not exclusive to nor always predictive of tool function, especially when considering the fact that many stone tools were multifunctional (Odell, 1981, Robertson et al., 2009, Stemp, n.d., Strathern, 1969, White, 1967).

As noted by Stemp et al. (2019:514), an important aspect of measuring edge angle, like any other ratio measurement, is scale. For the mathematical documentation of use-wear on stone tool surfaces, multi-scalar analyses have proven successful under experimental conditions (Key et al., 2015; Pfleging et al., 2019; Stemp et al., 2009, 2013, 2015a,b, 2018; Stemp and Chung, 2011). To date, only one experimental study (Stemp et al., 2019) has attempted to quantify edge angle/edge cross-section profiles using metrology over multiple area scales. In this study, Stemp et al. (2019) attempted the documentation of two-dimensional edge profile cross-sections on chipped stone tools made from basalt, chert, obsidian, and quartz using imaging confocal microscopy, laser scanning confocal microscopy, and focus variation microscopy. They found that only the basalt and chert tools' edges could be successfully measured using the focus variation technique when tool edge angles were greater than roughly 32°. The edge curvatures of the basalt and chert tools were then calculated over multiple scales using

the hybrid Heron's formula and Curvsoft (2017) (see Gleason et al., 2013, 2014). In a related study on machined metal edges, Bartkowiak and Brown (2019) presented multiscale 3D curvature analysis, which had been demonstrated on measurements of a cutting edge and machined surfaces made from metal. They found that large-scale features on the tool edge were transferred to the machined surface, whereas fine scale details on the tool were not. The 3D analysis allows characterization of principal curvatures (maximal and minimal) and directions at each location and scale. Although more difficult to calculate, multi-scalar 3D curvature analysis is better than multi-scalar 2D edge profile quantification for documenting edge features, such as gradient, divergence, and curl, and for identifying lay, or surface directionality (i.e., anisotropy), because it relies on surface data that can capture surface variations at different locations along an edge in three directions (i.e., x-, y-, and z-axes) (Brown et al., 2018: 855). This can be potentially useful in analyses of the nature of the changes in the tool geometry resulting from manufacturing or wear.

3. Materials

For the harvesting experiments, a set of Epipalaeolithic microliths were created and hafted into replica wooden hafts (Fig. 1). Fine-grained chert from the Negev, Israel, was chosen for the experimental knapping. This chert has an opaque to translucent appearance ranging from brown to grey in color. A set of microliths modeled after tools from the Middle Epipalaeolithic sites of Wadi Mataha, 'Uyun al-Hammâm, and Kharaneh IV were manufactured using indirect percussion with an antler punch and a hardwood billet by professional knapper Dodi Ben Ami for the harvesting experiment. They were then snapped and retouched with a bone spatula, pressing the spatula firmly down along the edge repeatedly to create straight backing. Subsequent retouch with the spatula was conducted to increase the invasiveness of the backing. The replicated tools were all trapeze-rectangle geometric microliths, with a mean length of 24.6 mm (std. dev. = 3.6; min = 19.9 mm; max = 31.9 mm), mean width of 9.4 mm (std. dev. = 1.0; min = 8.1 mm; max = 11.7 mm), a mean thickness of 3.6 mm (std. dev. = 0.7, min = 2.5 mm, max = 4.7 mm), and a mean edge angle of 34.9° (std. dev. = 2.5, min = 30°, max = 39°). This size is within the range of variability for similar archaeological Epipalaeolithic geometric microliths (see Macdonald, 2013).

Once the microliths were manufactured, they were hafted into wooden handles, carved by archaeologist and woodworker Dr. Dan Rahimi. Two identical wooden hafts were modeled after a bone artifact recovered from the Natufian deposits at Kebara Cave, Israel (Noy, 1991). This haft has been interpreted as a sickle, with the lithics inset lengthwise along the handle. The piece has a slightly arched profile,

curved forwards towards the front of the sickle, and has a zoomorphic ungulate head, perhaps representing a gazelle, at the grip end of the handle.

The two Kebara-style wooden sickles, one with seven inset microliths (EX14) and the other with six inset microliths (EX15), were used in the harvesting experiments (see below for details of the harvesting experiment). Initially, the microliths were set into the handles with bitumen. The bitumen was heated in a small pot over a burner, and warmed until the tar became very soft. The microliths were then dipped into the tar and inset into the haft. However, once harvesting commenced, one tool lost three microliths (EX14) when the bitumen softened due to heat generated by friction between the tool and the plant stems. As a result, the microliths in both tools were rehafted using pine resin that retained its hard consistency despite hours of use. The resin was collected in French coniferous forests by Dr. Bernard Gassin. To prepare the resin as a hafting material, sap was collected by hand from pine trees. The resin was mixed with wax over a hot stove, keeping it liquid. Once the sap and wax melted together, the mixture was poured over the haft with the microliths already inset. The resin hardened within 10 min, becoming solid and rigid.

In addition to the hafted microliths used for harvesting, several microliths were kept as examples of unused tools. These microliths were kept in individual sterile sample bags to minimize friction and 'bag wear'. These unused tools are used as a baseline for changes to the microliths after use.

4. Methods

The data collection for this project was undertaken in two stages; first, a series of harvesting experiments were conducted with the two Epipalaeolithic sickle replicas. Second, the edges of the tools were analyzed with focus variation microscopy to measure changes in the tool edge curvature with increasing use. The different methods are discussed below.

4.1. Harvesting experiments

In August 2011, one of the authors (Macdonald) participated in harvesting experiments in Southern France, organized and directed by Dr. Patricia Anderson. The experiments took place over five days, from August 22 to August 26, 2011, with three days dedicated to cutting the field, one to threshing the wheat, and one to winnowing the grain. The harvesting field was located outside the town of St. Vallier de Thieu (Alpes-Maritimes) and was planted with einkorn wheat (*Triticum monococcum*). This is one of the earliest cultivated and domesticated forms of wheat from Southwest Asia, allowing for a close analog to Epipalaeolithic harvesting practices (Heun et al., 1997).

The einkorn wheat (*Triticum monococcum*) was planted in a random pattern mimicking the growth pattern of wild cereals. The overall size of the field was approximately 630 m² but was parceled into smaller sections for each harvester. Einkorn wheat is an early Southwest Asian domesticated crop and has a similar breakage pattern to its wild progenitor. The field was planted very densely with wheat, with 792 stems per square meter. This is on the high end of wild cereal strands that usually have 600–800 stalks per square meter (Anderson, personal communication). There was an average of 19 spikelets per seed head. The overall grain yield was 15 kilos in total at the end of the harvest after threshing and winnowing.

The two Kebara-style sickles were used in the experiments; one was used by Macdonald (EX14) and the other by archaeologist Hatem El Gtari (EX15). Stroke counts were approximated by recording the average number of strokes cut per minute, averaged over 10 harvesting episodes at the beginning of each day. The average number of strokes for Macdonald's harvesting was 30 strokes per minute, while the average for El Gtari, who was a more vigorous harvester, was 59 strokes per minute (Table 1).

Experiment 14 (EX14) was conducted using a Kebara-style haft with seven hafted microliths. Microliths 1–3 (with 1 being closest to the handle) became dislodged as a result of the bitumen hafting and were re-hafted with resin. To cut the wheat stalks, a handful of approximately 7–10 stems were collected in Macdonald's left hand (Fig. 2). The stems were then twisted half a turn, bundling the stems together into a group. Two to three fast strokes with the sickle were required to cut through the bundle, pulling the sickle towards the user in a smooth motion. Cutting was done close to the ground, approximately 20–30 cm from the soil surface. In total, the sickle was used for approximately 12,150 strokes (405 min of cutting) over three days. The total field size harvested during this time was 78 m².

Experiment 15 (EX15) was also conducted using a Kebara-style sickle, but this experiment was performed by El Gtari. The microliths in this sickle were originally hafted with bitumen but were reset using resin at the same time as the microliths in the other sickle were re-hafted. In total, this sickle was used for approximately 19,234 strokes, equaling 326 min of harvesting time. The total field size harvested with this sickle was 84.25 m².

The results of the experiments indicated that the hafted microliths were very efficient harvesting tools. The regular size and shape of the flint implements allowed them to function without breaking, catching stems, or falling out of the handle while harvesting. The Kebara-style hafts were ergonomic, fitting comfortably into the hand without causing fatigue. The ungulate head (gazelle?) functioned to keep the harvester's hand from slipping off the end of the tool while vigorously cutting wheat, suggesting that the zoomorphic design had a functional purpose in addition to its decorative characteristics. After three days and > 12,000 strokes, the tools were still effective for cutting grain stems (although the harvester was feeling fatigued).

4.2. Focus variation microscopy

The application of engineering principles and technologies to measure stone tool surfaces has rapidly increased over the last 10–15 years (Calandra et al., 2019a, Ibáñez et al., 2019, Stemp et al., 2016). Although there were attempts by archaeologists to quantify stone tool surfaces in the late 1970s – early 1980s based on tribology/metrology, their results, although informative about the techniques, were generally not very reliable for lithic surface assessment (e.g. Bauch, 1984; Beyries et al., 1988; Dumont, 1982). Significant strides toward the quantification of lithic microwear began around the turn of the past millennium (Anderson et al., 1998, Kimball et al., 1998, Kimball et al., 1995, Stemp and Stemp, 2001, Stemp and Stemp, 2003, Vargiolu et al., 2007) with an increase in the number and the overall success of experimental approaches, in part due to improvements in the microscopes and surface measurement algorithms/parameters themselves. More recently, archaeologists have explored a wider range of microscopes equipped with measurement systems to mathematically document the surfaces of stone tools on micrometer and nanometer scales. To date, those that archaeologists have mainly employed include atomic force microscopy (Faulks et al., 2011, Kimball et al., 2017), interferometry (Anderson et al., 2006, Kimball et al., 2017), laser profilometry (Stemp, 2014, Stemp et al., 2010, Stemp et al., 2009), laser scanning confocal microscopy (Evans and Donahue, 2008, Evans and Macdonald, 2011, Evans et al., 2014, Macdonald et al., 2018, Stemp et al., 2015a, Stemp and Chung, 2011, Stemp et al., 2013, Stemp et al., 2018, Stemp et al., 2019, Werner, 2018), white-light scanning confocal microscopy (Ibáñez et al., 2019), imaging confocal microscopy (Macdonald et al., 2019, Stemp et al., 2019), and focus variation microscopy (Evans and Macdonald, 2011; Macdonald, 2014; Pfleging et al., 2019; Stemp et al., 2019). Once acquired using these measurement systems, the surface roughness/texture data have primarily been processed using algorithms/parameters that conform to the professional industrial manufacturing standards of the American Standards of Mechanical Engineers, specifically AMSE B46.1 (2009), and the

Table 1

Details of the Experimental Tools used in the harvesting experiments.

Ex. #	Date of Experiment	Participant	Location of Experiment	# of inset microliths	Contact Material	Stroke Angle °	Direction of use	# of Strokes
EX14	24/08/2011	Macdonald	St. Vallery du Theirry, France	7 (replica Kebara haft)	einkorn wheat	45–90	one-way	12,150
EX15	24/08/2011	El Gtari	St. Vallery de Theirry, France	6 (replica Kebara haft)	einkorn wheat	45–90	one-way	19,234
Unused	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0

**Fig. 2.** D. Macdonald harvesting einkorn wheat (*Triticum monococcum*) in southern France.

International Organization of Standardization, specifically ISO 25178–2 (2012).

The microlith inserts in this study were analyzed with focus variation microscopy using a Sensofar S neox microscope. This microscope is designed for precision engineering and surface metrology fields; however, it is used by a wide range of disciplines, including anthropology and archaeology, to measure small scale surface topographies at the scale of micrometers and nanometers (e.g. Aliaga-Martínez et al., 2017, Caux et al., 2018, Henshilwood et al., 2018, McGrath et al., 2018, Ragni et al., 2017, Ungar and Berger, 2018). Using the Sensofar, three scans were taken along each tool to capture the edge angle, with scan ‘a’ located on one end, scan ‘b’ in the middle, and scan ‘c’ on the furthest end (Fig. 1). In total, measurements from five microliths hafted in EX14 were taken, totaling 15 measurements from this composite tool. From EX15, four microliths were scanned, totaling 12 measurements from this experimental composite tool. The edge curvature from two different unused tools were measured, Unused-1 and Unused-2, with three measurements per tool, totaling 6 measurements of unused edges.

Scans were taken with focus variation microscopy mode on the Sensofar S neox, and measurements were taken in 3D expert mode, raw smoothing: 1. Scans were taken with both the 20 × objective (NA 0.45) and the 50 × objective (NA 0.80). Images were first taken with the 20 × objective. Next, the 50 × objective was moved into position so the scan could be taken at the same location. The area using the 20 × objective is $877.2 \times 660.48 \mu\text{m}^2$, $0.64 \mu\text{m}/\text{pixel}$. For the 50 × objective, it is $350.88 \times 264.19 \mu\text{m}^2$, $0.26 \mu\text{m}/\text{pixel}$. Both were taken at the highest resolution (HD 4). The z-scan range is approximately $500 \mu\text{m}$ for the 20 × objective. For the 50 × objective, the z-scan resolution is $150 \mu\text{m}$. Speed was set to 1 ×. The threshold was set at 1 to allow for the most data to be collected. Measurement outliers were removed using the automatic algorithm incorporated in Sensofar instruments.

After measurements were taken with the Sensofar, data was imported into MountainsMap 8 (Digital Surf, France) software. Prior to

data analysis, non-measured regions were filled with smooth surfaces. Curvature calculation required an estimate of surface normal vectors. This was based on one central point and the eight most proximal points to that central position. Presence of unmeasured regions leads to the situation in which calculation of curvature might not be possible for a significant number of patches as one or more points are missing. Filling the non-measured regions can be considered controversial, as the further analysis involves regions that were not physically measured but extrapolated based on the adjacent points. However, it does not necessarily influence the quality of the results as there are numerous examples in which strong correlations were found between topographic curvature and phenomena of interest despite filling the unmeasured regions (Bartkowiak et al., 2018, Bartkowiak and Brown, 2019). In the presented case, each measurement was inspected visually after filling non-measured regions to determine whether the resultant surface was free of artificially-created doubtful features. The original datasets were then cropped to $262.64 \mu\text{m} \times 129.00 \mu\text{m}$ (1018×500 points) for the 50 × objective and $656.61 \mu\text{m} \times 348.30 \mu\text{m}$ (1018×540 points) for the 20 × objective. For some very steeply sloped edges, only a middle part of the measurement area, representing the edge topography, was measured; whereas, the lateral regions were not captured by the Sensofar and were, therefore, unmeasured (i.e., heights were zero). This was caused by the limitation of maximum measurement depth, which is an inherent feature of the microscopic measurement. The area cropping was aimed at removing those regions from the analysis. For each cropped area measurement, the arbitrary edge line was parallel to the x-axis and the top of the edge (intersection of the dorsal and ventral faces) was placed centrally with respect to the y-axis. These modifications were done manually for all measurements. The measurements were exported to ASCII files as lists of x, y, z coordinates. They were then processed with the curvature script run in Mathematica (Wolfram Research, UK) software (this script is available upon request). The analysis was performed for scales ranging from $1 \times$ to $39 \times$ the original

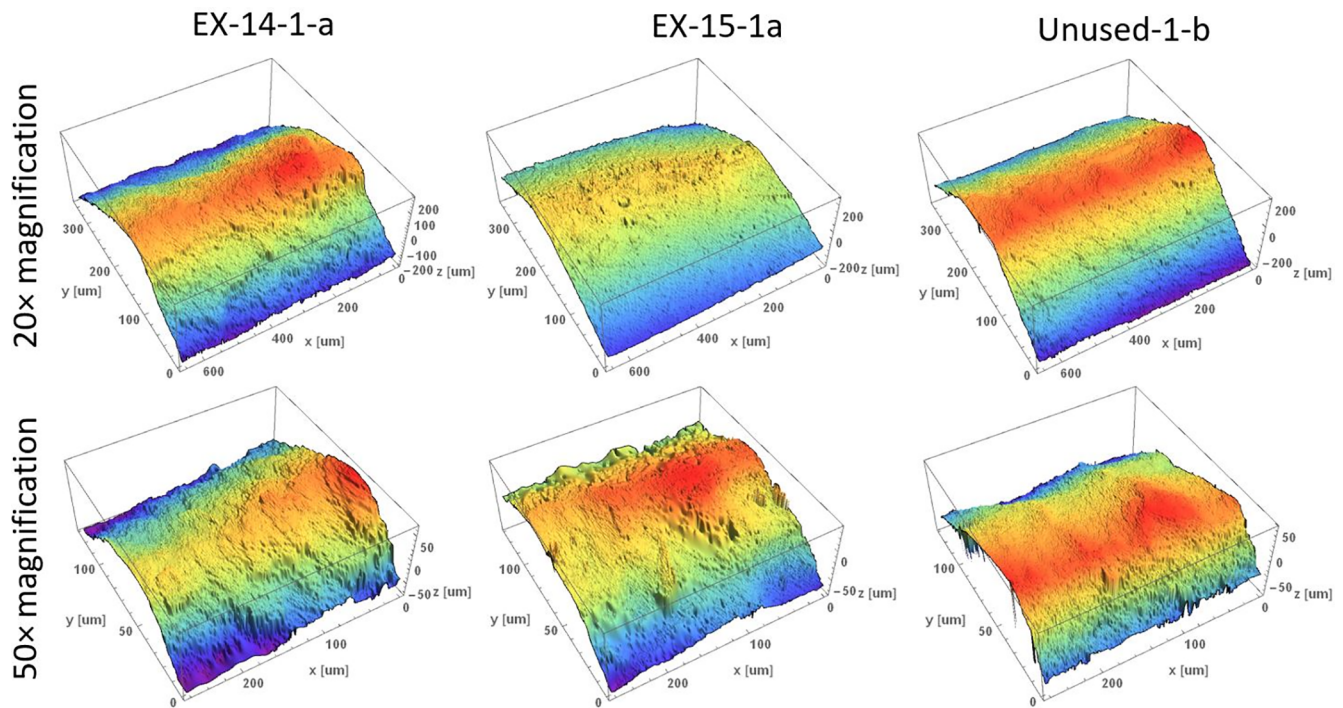


Fig. 3. Renders of topographic measurements illustrating the top of the cutting edge of three different specimens captured at 20× and 50× magnifications.

sampling intervals, with a 2 × increment. In this preliminary study, only maximum and minimum curvatures were considered, but the script allows for calculation of mean and Gaussian curvatures as well.

4.3. 3D multiscale curvature analysis

In this study, we calculate curvature from an areal measurement (i.e., on regular orthogonal arrays of heights, z , in x and y , such that $z = z(x,y)$) and characterize it as a second order tensor, which can vary with position and scale. This research differs from the work by Stemp et al. (2019) in that it analyses edge curvature in three-dimensional space, rather than calculating edge curvature in two-dimensional cross-sections. The advantage of calculations in three dimensions is that these calculations are less sensitive to deviations and anomalies on the tool's edge, thus better capturing the overall edge curvature of the tool. Curvature tensor T can be denoted as:

$$T = PDP^{-1} \quad (1)$$

where $P = (\mathbf{k}_1, \mathbf{k}_2, \mathbf{n})$ and

$$D = \begin{pmatrix} \kappa_1 & 0 & 0 \\ 0 & \kappa_2 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (2)$$

where κ_1 and κ_2 are principal maximum and minimum curvatures [$\mathbf{k}_1$ and $\mathbf{k}_2$ are the principal directions around which a surface bends the most and the least; $\mathbf{n}$ is a normal vector perpendicular to both principal directions]. These five constituents (κ_1 , κ_2 , $\mathbf{n}$, $\mathbf{k}_1$, and $\mathbf{k}_2$) are needed to fully characterize curvature at each location and scale. The description of how to calculate these parameters can be found in Bartkowiak and Brown (2019). The benchmark of existing multiscale curvature estimation techniques was established by Maleki et al. (2019). They showed that the method we present here is a credible and valuable tool for analyzing surface microtopography.

Similar to heights analysis, distributions of principal, mean, and Gaussian curvature can be derived, and statistical parameters can be calculated, from those distributions. At any location and scale, the mean curvature (H) is the sum of the two principal curvatures divided by two and the Gaussian curvature (K) is the product of the two

principal curvatures. Average and standard deviation curvature parameters were defined by Bartkowiak et al. (2018). These are similar to the height parameters, and are calculated in the usual way, although at particular scales and locations. In this study, we concentrate on calculating principal maximal and minimal curvatures to determine which parameter better characterizes the cutting edge geometry and at what scale. This is quantified by using κ_{1a} and κ_{2a} .

In the multiscale curvature analysis, the scale is connected with the size of the individual region for which curvature is determined. This region is called a patch and each patch is a right-angled (also isosceles if sampling interval in x and y are the same, as in this study) triangle when projected on the datum (xy -plane). The side of the triangle is associated with the scale. The finest possible scale is equal to the original sampling interval – 0.645 μm for 20× magnification and 0.258 μm for 50×. The size of the patch and, thus, scale can only be modified by multiplying the sampling interval by a natural number, e.g. scales 1.290, 3.225, 6.450 μm , were created by multiplying 0.645 μm (original sampling interval for surfaces captured with 50× magnification lens) by 2, 5, and 10. The description of the method and how the scale is calculated is demonstrated in Bartkowiak and Brown (2018, 2019).

5. Results

Curvature tensor scalar parameters – maximal (κ_1) and minimal (κ_2) curvatures – were calculated for scales from 0.645 to 32.250 μm for measurements taken with the 20× objective and between 0.258 and 12.900 μm for measurements using the 50× objective. The range of those scales is between 1 × and 50 × the original sampling interval. The original measurements were each trimmed to 540 × 1018 points in order to maintain the same region size for the curvature analysis. The top of the cutting edge was placed in the center of that region. Renders of representative measurements from all three specimens are depicted in Fig. 3.

The principal curvatures indicate the amount by which a surface bends the most or the least. For an infinitely sharp and perfectly straight edge, the maximum curvature would tend to infinity; whereas, minimum curvature would be zero. For an ideally flat surface, both

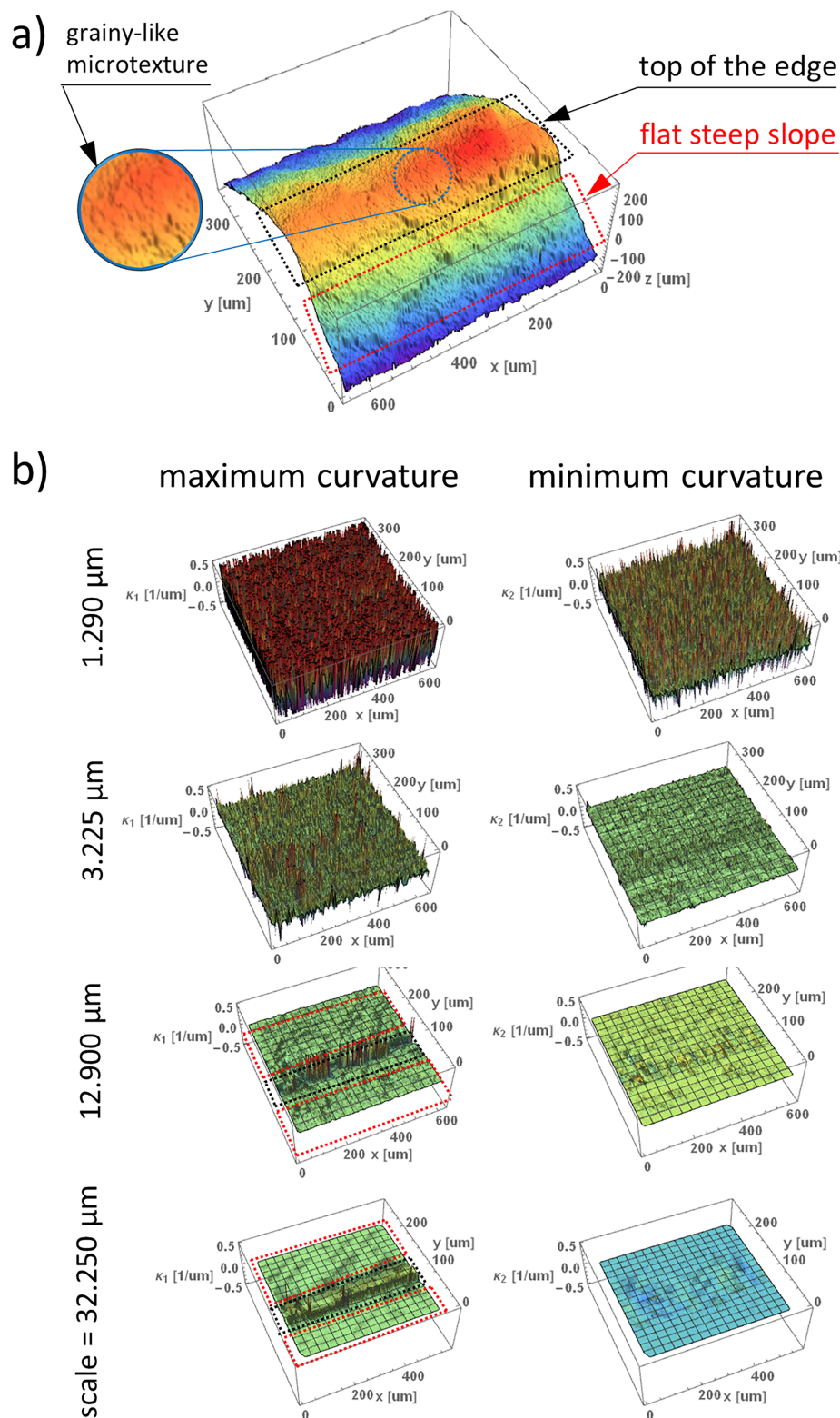


Fig. 4. a) Topography of the tool edge with the microtexture, top of the edge, and the slopes identified [top of the edge is indicated by a black outline, while the slopes are indicated with a red outline]; b) Maximum curvature κ_1 and minimum curvature κ_2 calculated for EX14-1-a, measured with $20\times$ magnification lens, calculated at scales of 1.290, 3.225, 6.450, 12.900 and 32.250 μm (on each graph, x and y coordinates are in μm, z axis is curvature in $1/\mu\text{m}$).

principal curvatures are null. The sign – positive or negative – of the principal curvature is indicative of local convexity or concavity. At any particular scale, if at some location both principal curvatures are positive, then this location is the bottom of a pit at that scale. If both are negative at some location, then this is a peak at that scale. And, if one

principal curvature is positive and the other is negative, it represents a saddle shape at that scale.

The results of curvature analysis can be illustrated in an areal map representing the values of principal curvatures at each location. Maximum curvature κ_1 and minimum curvature κ_2 for EX14-1-a

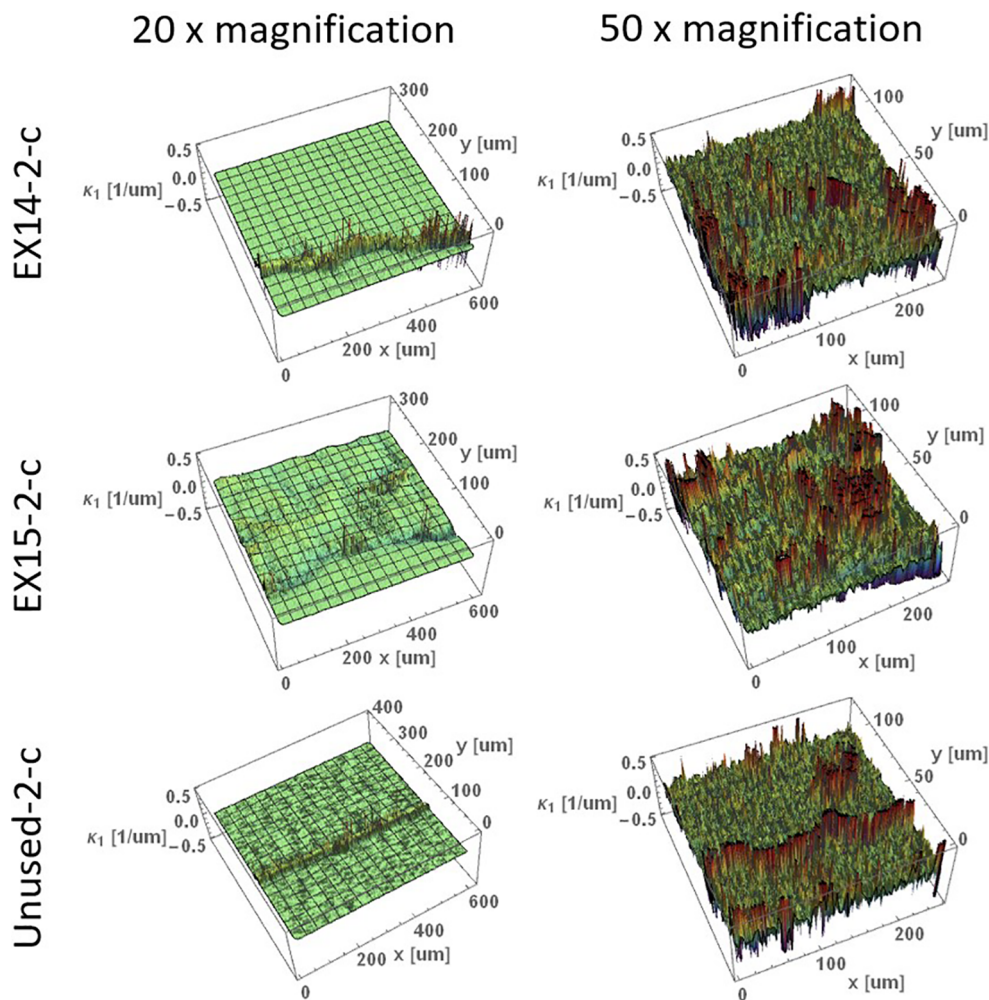


Fig. 5. Comparison of maximum curvature κ_1 for EX14-2-c, EX15-2-c and Unused-2-c calculated at a scale of 12.900 μm captured with the 20 $\times$ magnification lens (right column) and a scale of 12.900 μm (left column) captured with the 50 $\times$ lens (on each graph, x and y coordinates are in μm , z axis is curvature in 1/ μm).

measured at 20 $\times$ magnification calculated at scales of 1.290, 3.225, 6.450, 12.900 and 32.250 μm are shown in Fig. 4. Blue corresponds to negative maximal curvatures and red to positive ones. The magnitude of maximum curvature is higher than minimum curvature for the corresponding scales and it decreases with increasing scales. At the largest scale, the edges appear to be “smoother”, which is reflected in the lower values of curvatures. With decreasing scale of calculation, the surface across the edge is captured in more detail and seems to be “rougher”.

At fine scales, a multitude of small surface features that have large principal κ_1 curvatures ‘masks’ the curvature along the stone tool edge (point of intersection of the sloped surfaces) (Fig. 5). As such, the edge of the tool cannot be mathematically discriminated from the sloped surfaces that intersect to form the edge itself. The curvature of the stone tool edge becomes evident as the scale of calculation increases. This is due to the fact that the tool edge’s maximum curvature has a higher magnitude than the ‘background’ maximum curvature, which incorporates the sloped surfaces further away from the point of intersection at the edge. Minimum curvature κ_2 can also document a similar phenomenon, but it is less evident as minimum curvature is more uniformly distributed (in terms of its magnitude) on both sloped surfaces and along the edge itself.

The variation of tool geometry represented by the topographic data leads to differences in their curvature distributions. Fig. 5 depicts a comparison of maximum curvature κ_1 for EX14-2-c, EX15-2-c and Unused-2-c calculated at the identical scale of 12.900 μm captured with both magnification lenses. For the same calculation scales, curvature

produces higher values for the 50 $\times$ than the 20 $\times$ objective. This might suggest that measurements taken at higher magnification capture more topographic details, specifically the fine scale features, than those taken at lower magnification. This is in keeping with research by Calandra et al. (2019b) which demonstrates that the numerical aperture of objectives can impact the measurement of surface texture.

For the measurements taken with the 20 $\times$ objective, there is a local minimum for the κ_1 value at the 10.965 μm scale for EX14. This is due to the fact that the edge was not completely filling the measurement area leaving some unmeasured regions on both slopes (Fig. 6). This was caused by the inability to illuminate the lowest regions of the slope making it impossible to document them using the microscope. For scales around 10.965 μm , the curvature of the top regions, as well as the transition between the unmeasured region and slopes, become the most evident. For the finest scales, higher curvature of fine scale details mitigate this effect. For larger scales, this region is not measured because the calculation window becomes smaller. As such, it does not incorporate the lowest regions. This effect was not observed for measurements taken at 50 $\times$ magnification as the measurement region was smaller and the difference in heights was not significant enough to generate unmeasured points.

The key issue in this and future studies would be to determine at which scales of calculation edge sharpness, edge attrition, and micro-wear can be best documented, correlated, and discriminated. This can be potentially addressed by calculating statistical parameters for distributions of principal curvatures at each scale. Fig. 7 shows average

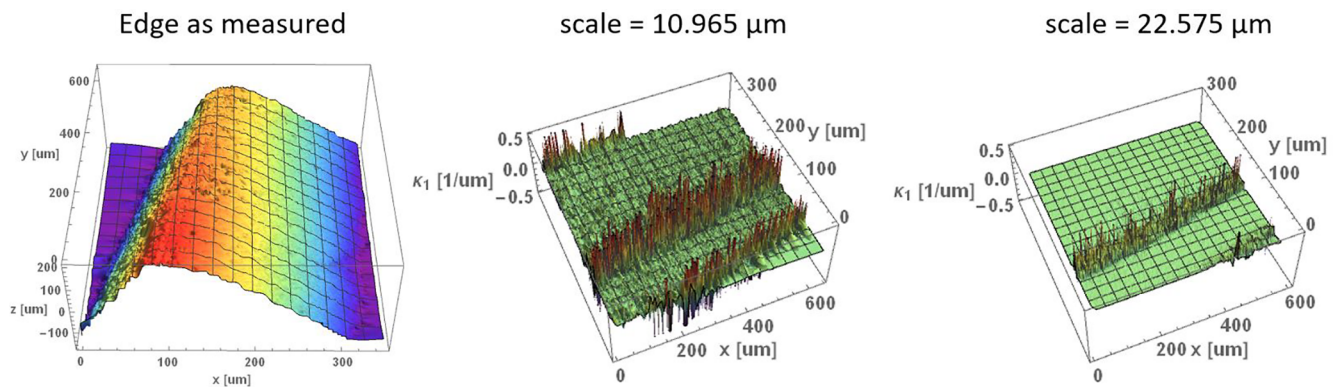


Fig. 6. Measurements of EX14-4-c taken at $20\times$ magnification and maximum principal curvature calculated for scales 10.965 and 22.575 μm showing the effect of the presence of the unmeasured region on the calculated curvature.

maximum curvature (κ_1a) calculated for all the specimens as a function of scale. The general edge shape is convex, which is evident in the negative values of average curvature. The curvature of the unused edge has lower values than the curvature of the other two experimental microliths. This occurs at larger scales ($> 7.095 \mu\text{m}$ for $20\times$ and $> 2.332 \mu\text{m}$ for $50\times$). The reliability of the analysis results at the finest scales might be limited due to the presence of measurement noise, which may obscure curvature.

For EX14, at $\times 20$ magnification, average maximum curvature takes the minimum at a scale of 10.965 μm . This is caused by the presence of convex features (of negative maximum curvature) located on the top of the edge whose shape becomes evident around that scale. This causes the average value of the curvature calculated for the entire measurement to decrease. The sudden change in average curvature for larger scales is caused by the fact that the effect of those features disappear. No such features were observed in EX15. The larger the scale, the less the number of fine scale features with high positive curvatures could be characterized. This causes the average value of maximum curvature to have higher negative numbers with scale.

The results for $20\times$ magnification at scales $> 16.125 \mu\text{m}$ indicate that the average maximum curvature is the lowest for the Unused microliths (Fig. 7a). The magnitude of average maximum curvature is higher for EX14 and the highest for EX15. This could be correlated with the duration of use, meaning that the cereal harvesting activities created high curvature features which can be observed at the calculation scale $> 16.125 \mu\text{m}$. The same correlation with duration of use is evident in average values of maximum curvature calculated for scales between 1.806 and 6.966 μm for microliths measured with the $50\times$ objective. At larger scales, average values of κ_1a for EX14 and

EX15 are similar (Fig. 7b).

6. Discussion and conclusion

Understanding tool function in the past, including harvesting tools, gives us greater insight into the behaviors and cultural patterns of past peoples. The driving forces behind the origins of agriculture are an enduring question in archaeological research, and deeper knowledge into how early agricultural tools were used during this pivotal transition in subsistence practices. As such, experiments involving microwear analysis of tool edges on chert microliths, using novel methods derived from surface metrology, have the potential to provide significant information about tool use in the past, and specifically in this case, use duration.

Based on the results of this first ‘proof-of-concept’ experiment, there were a number of interesting observations. First, focus variation microscopy can be used to measure the areas along edge cross-sections of stone tools made from silicates, in this case fine-grained chert. These results provide support for the same observation made by Stemp et al. (2019) using focus variation to measure the edges of chert tools. Second, the results of this experiment confirm another observation made by Stemp et al. (2019) that focus variation microscopy could successfully document stone tool edges (basalt and chert) with steep slopes, specifically above a $\sim 32^\circ$ edge angle threshold. Third, principal maximum and minimum edge curvatures can be calculated over multiple scales using the measurements taken on stone tool edges. Fourth, the maximum curvature κ_1 cannot be accurately documented on the stone tool edges at the finest scales because the surface of the edge itself cannot be discriminated from the sloped surfaces on either side of it.

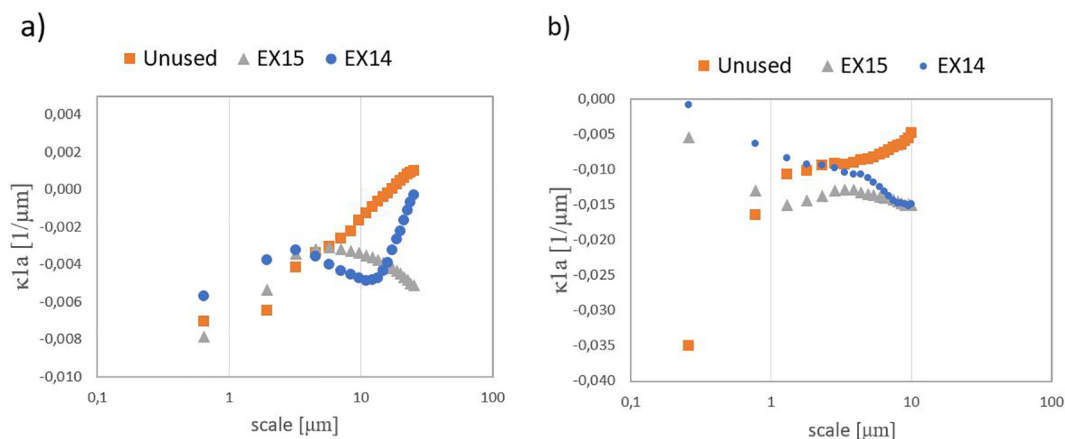


Fig. 7. Average value of principal maximum curvature as a function of scale calculated for all three specimens measured with a) $20\times$ magnification and b) $50\times$ magnification lenses.

However, the maximum curvature κ_1 of the stone tool edge can be determined as the scale of calculation increases. Fifth, although minimum curvature κ_2 also demonstrates a similar phenomenon, the ability to discriminate the tool edge from the sloped sides is less significant. These results suggest that maximum curvature κ_1 is a more reliable parameter than minimum curvature κ_2 for documentation of the tool edge in this experiment. Sixth, there are differences in curvature values that are caused by the differences in magnification between the 20x and 50x objectives. Whether this is due to the optics of the lenses (i.e., numerical aperture), signal processing, or some other aspect of the physics involved is not known at this time. Nevertheless, the curvatures calculated using measurements with the 20x objective appear to have fewer surface details and are less “rough” than those produced with the 50x objective. To better understand the role of the objectives in affecting the curvature values, the fidelity of measurements could be tested by looking at statistical correlations between characterization parameters (e.g. average maximum curvature, minimum curvature) and performance parameters (e.g., processing time, wear value, etc.). Seventh, using a novel method to calculate edge curvature, this paper provides preliminary results that, at certain scales for both the 20 × and 50 × objectives, the edges of chert harvesting tools possess larger average maximum curvatures with increased duration of use. As such, the average maximum curvature of microlith edges may be a reliable quantitative measure correlated with use duration.

The calculation of maximal and minimal edge curvatures offers a new and potentially powerful method to quantify use duration of stone tools. To confirm this, future experiments using focus variation microscopy and edge curvature analysis will need to incorporate the addition of more tools, additional measurements of the tools before use, and the use of the tools over many more varying timescales. As the sample size in the study was small, and the intervals of use close together, increasing the number of experiments and adding several additional steps in the duration of use is necessary to fully understand how edge curvature changes over time. This would provide the larger datasets necessary to verify what level of magnification and what scale of characterization generate the most reliable correlations between use-duration and edge curvature. Ongoing research using these calculations can continue to test the power of this method on experimental, as well as archaeological, tools to explore the function of harvesting tools in the past. Furthermore, this method may be more broadly applicable to a range of experimental and archaeological materials, allowing for new methods of quantification of edge curvature for a multitude of material culture types.

CRedit authorship contribution statement

Danielle A. Macdonald: Conceptualization, Investigation, Resources, Writing - original draft. **Tomasz Bartkowiak:** Conceptualization, Methodology, Formal analysis, Writing - original draft. **W. James Stemp:** Conceptualization, Writing - original draft.

Acknowledgements

Macdonald would like to thank Dr. Patricia Anderson for organizing and inviting her to participate in the experimental harvesting, it was a wonderful experience to be part of the experiments. Thank you as well to Hatem El Gtari who participated in the experimental harvesting and used sickle EX15. Thank you to Dodi Ben Ami for knapping the replica microliths and Dr. Dan Rahimi for constructing the beautiful hafts. Access to the Sensofar S neoX microscope was provided by Dr. Miriam Belmaker at the University of Tulsa. Funding for Macdonald was provided by National Science Foundation Grant #1727357. Funding for Bartkowiak was provided by Polish Ministry of Science and Higher Education as a part of research subsidy SBAD.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2020.102523>.

References

- Aliaga-Martínez, A., Romero, A., Galbany, J., Hernández-Aguilar, R.A., Pérez-Pérez, A., 2017. Buccal dental microwear texture and catarrhine diets. *Am. J. Phys. Anthropol.* 163 (3), 462–473.
- Anderson, P., 1983. A Consideration of the Uses of Certain Backed and “Lustered” Stone Tools from Late Mesolithic and Natufian Levels of Abu Hureyra and Mureybet (Syria). In: Cauvin, J. (Ed.), *Traces d’Utilisation sur les Outils Néolithiques du Proche Orient*, Maison de l’Orient. Paris, pp. 77–106.
- Anderson, P., 1991. Harvesting of Wild Cereals During the Natufian as Seen from the Experimental Cultivation and Harvest of Wild Einkorn Wheat and Microwear Analysis of Stone Tools. In: Bar-Yosef, O., Valla, F. (Eds.), *The Natufian Culture in the Levant*. International Monographs in Prehistory, Michigan, pp. 521–556.
- Anderson, P., Astruc, L., Vargiolu, R., Zahouani, H., 1998. Contribution of quantitative analysis of surface states to a multi-method approach for characterising plant-processing traces on flint tools with gloss. In: *Functional Analysis of Lithic Artefacts: Current State of the Research*, XIII International Congress of Prehistoric and Protohistoric Sciences. Workshops, Tome II, ABACO Edizioni, Forlì, pp. 1151–1160.
- Anderson, P.C., Georges, J.-M., Vargiolu, R., Zahouani, H., 2006. Insights from a tribological analysis of the tribolum. *J. Archaeol. Sci.* 33 (11), 1559–1568.
- Anderson, P., Valla, F., 1996. Glossed tools’ from Hayonim Terrace: blank choice and functional tendencies S.K. In: Kozłowski, H. (Ed.), *Gebel Neolithic Chipped Stone Industries of the Fertile Crescent and their Contemporaries in Adjacent Regions*. ex Oriente, Berlin, pp. 341–362.
- Bar-Yosef, O., 1998. The Natufian culture in the Levant, threshold to the origins of agriculture. *Evol. Anthropol.* 6 (5), 159–177.
- Bar-Yosef, O., Belfer-Cohen, A., 1991. From Sedentary Hunter-Gatherers to Territorial Farmers in the Levant. In: Gregg, S. (Ed.), *Between Bands and States*. Center for Archaeological Investigations, Carbondale, pp. 181–202.
- Bartkowiak, T., Berglund, J., Brown, C.A., 2018. Establishing functional correlations between multiscale areal curvatures and coefficients of friction for machined surfaces. *Surf. Topogr.: Metrol. Prop.* 6, 034002.
- Bartkowiak, T., Brown, C.A., 2018. A characterization of process-surface texture interactions in micro-electrical discharge machining using multiscale curvature tensor analysis. *J. Manuf. Sci. Eng.* 140 (2). <https://doi.org/10.1115/1.4037601>.
- Bartkowiak, T., Brown, C.A., 2019. Multiscale 3D curvature analysis of processed surface textures of aluminum alloy 6061 T6. *Materials* 12 (2), 257. <https://doi.org/10.3390/ma12020257>.
- Bauch, R., 1984-1986. Die anwendung von rauheitsmessungen bei der untersuchung von neolithischen mahl- und schleifsteinen. *Early Man News* 9 (10/11), 51–67.
- Belfer-Cohen, A., 1995. Rethinking Social Stratification in the Natufian Culture: The Evidence from Burials. In: Campbell, S., Green, A. (Eds.), *The Archaeology of Death in the Ancient Near East*. Oxbow Books, Oxford, pp. 9–16.
- Beyries, S., Delamare, F., Quantin, J.-C., 1988. Traceologie et Rugosimetrie Tridimensionnelle. In: Beyries, S. (Ed.), *Traceologie et Technologie: Aspects Methodologiques*. BAR International Oxford, pp. 115–132.
- Bordes, F., 1961. The Mousterian Cultures of France. *Science* 134, 803–810.
- Borel, A., Gaillard, C., Moncel, M.-H., Sala, R., Pouydebat, E., Simanjuntak, T., Sémah, F., 2013. How to interpret informal flakes assemblages? Integrating morphological description, usewear and morphometric analysis gave better understanding of the behaviors of anatomically modern human from Song Terus (Indonesia). *J. Anthropol. Archaeol.* 32 (4), 630–646. <https://linkinghub.elsevier.com/retrieve/pii/S0278416513000172>.
- Broadbent, N., Knutsson, K., 1975. An experimental analysis of quartz scrapers: results and applications. *Fornvännen* 70, 113–128.
- Brown, C.A., Hansen, H.N., Jiang, X.J., Blateyron, F., Berglund, J., Senin, N., Bartkowiak, T., Dixon, B., Le Goïc, G., Quinsat, Y., Stemp, W.J., Thompson, M.K., Ungar, P.S., Zahouani, E.H., 2018. Multiscale analyses and characterizations of surface topographies. *CIRP Ann.* 67 (2), 839–862.
- Büller, H., 1983. Methodological Problems in the Microwear Analysis of Tools Selected from the Natufian Sites of El Wad and Ain Mallaha. In: Cauvin, J. (Ed.), *Traces d’Utilisation sur les Outils Néolithiques du Proche Orient*, Maison de l’Orient. Paris, pp. 107–125.
- Byrd, B.F., 2005. Reassessing the emergence of village life in the Near East. *J. Archaeol. Res.* 13 (3), 231–290.
- Calandra, I., Pedergrana, A., Gneisinger, W., Marreiros, J., 2019a. Why should traceology learn from dental microwear, and vice-versa? *J. Archaeol. Sci.* 110, 105012. <https://doi.org/10.1016/j.jas.2019.105012>.
- Calandra, I., Schunk, L., Bob, K., Gneisinger, W., Pedergrana, A., Paixao, E., Hildebrandt, A., Marreiros, J., 2019b. The effect of numerical aperture on quantitative use-wear studies and its implication on reproducibility. *Sci. Rep.* 9 (1). <https://doi.org/10.1038/s41598-019-42713-w>.
- Caux, S., Galland, A., Queffelec, A., Bordes, J.-G., 2018. Aspects and characterization of chert alteration in an archaeological context: A qualitative to quantitative pilot study. *J. Archaeol. Sci.: Reports* 20, 210–219.
- Collins, S., 2008. Experimental investigations into edge performance and its implications for stone artefact reduction modelling. *J. Archaeol. Sci.* 35 (8), 2164–2170.
- Dibble, H.L., 1995. Middle Paleolithic scraper reduction: Background, clarification, and review of the evidence. *J. Archaeol. Method Theory* 2, 299–368.

- Dumont, J., 1982. The quantification of microwear traces: A new use for interferometry. *World Archaeol.* 14 (2), 206–217.
- Eren, M.I., 2013. The technology of Stone Age colonization: an empirical, regional-scale examination of Clovis unifacial stone tool reduction, allometry, and edge angle from the North American Lower Great Lakes region. *J. Archaeol. Sci.* 40 (4), 2101–2112.
- Eren, M.I., Lycett, S.J., 2016. A statistical examination of flake edge angles produced during experimental lineal Levallois reductions and consideration of their functional implications. *J. Archaeol. Method Theory* 23 (1), 379–398.
- Evans, A.A., Donahue, R.E., 2008. Laser scanning confocal microscopy: A potential technique for the study of lithic microwear. *J. Archaeol. Sci.* 35 (8), 2223–2230.
- Evans, A.A., Macdonald, D., 2011. Using metrology in early prehistoric stone tool research: Further work and a brief instrument comparison. *Scanning* 33, 294–303.
- Evans, A.A., Macdonald, D.A., Giusca, C.L., Leach, R.K., 2014. New method development in prehistoric stone tool research: Evaluating use duration and data analysis protocols. *Micron* 65, 69–75.
- Faulks, N., Kimball, L.R., Hidjati, N., Coffey, T., 2011. Atomic force microscopy of microwear traces on Mousterian tools from Myshtylagty Lagat (Weasel Cave) Russia. *Scanning* 33, 304–315.
- Fellner, R., 1995. Technology or typology?: A response to Neeley and Barton. *Antiquity* 69, 381–383.
- Gleason, M.A., Kordell, S., Lemoine, A., Brown, C.A., 2013. Profile curvatures by Heron's formula as a function of scale and position on an edge rounded by mass finishing. In: 14th International Conference on Metrology and Properties of Engineering Surfaces TS4-01, pp. 0022.
- Gleason, M.A., Lemoine, A., Brown, C.A., Morgan, C., 2014. Multi-scale calculation of curvatures from an aspheric lens profile using Heron's formula. In: Proceedings ASPE/ASPEN, Summer Topical Meeting, Manufacture and Metrology of Freeform and Off-Axis Aspheric Surfaces, June 26–27, American Society for Precision Engineering, pp. 98.
- Goodale, N., Otis, H., Andrejsky Jr., W., Kuijt, I., Finlayson, B., Bart, K., 2010. Sickle blade life-history and the transition to agriculture: An early Neolithic case study from Southwest Asia. *J. Archaeol. Sci.* 37 (6), 1192–1201.
- Goring-Morris, A.N., 1996. Square pegs into round holes: A critique of Neeley and Barton. *Antiquity* 70, 130–135.
- Gould, R.A., Koster, D.A., Sontz, A.H.L., 1971. The lithic assemblages of the Western Desert aborigines of Australia. *Amer. Antiq.* 36, 149–169.
- Grosman, L., Munro, N.D., Belfer-Cohen, A., 2008. A 12,000-year-old Shaman burial from the southern Levant (Israel). *Proc. Natl. Acad. Sci.* 105 (46), 17665–17669.
- Hayden, B., 1977. Stone Tool Function in the Western Desert. In: Wright, R.V.S. (Ed.), *Stone Tools as Cultural Markers: Change, Evolution, and Complexity*. Australian Institute of Aboriginal Studies, Canberra, pp. 178–188.
- Hayden, B., 1979. Snap, Shatter, and Superfractures: Use-Wear of Stone Skin Scrapers. Academic Press, New York, *Lithic Use-Wear Analysis*, pp. 207–229.
- Henshilwood, C.S., d'Errico, F., van Niekerk, K.L., Dayet, L., Queffelec, A., Pollaro, L., 2018. An abstract drawing from the 73,000-year-old levels at Blombos Cave, South Africa. *Nature* 562 (7725), 115–118.
- Heun, M., Scafer-Pregl, R., Klawan, D., Castagna, R., Accerbi, M., Borghi, B., Salamini, F., 1997. Site of einkorn wheat domestication identified by DNA fingerprinting. *Science* 278, 1312–1314.
- Hurcombe, L., 1992. *Use Wear Analysis and Obsidian: Theory, Experiments and Results*. Collis Publications, University of Sheffield, Sheffield, J.R.
- Ibáñez, J.J., 2008. Le site Néolithique de Tell Mureybet (Syrie du Nord). British Archaeological Report, International Series, Archaeopress, Oxford, En hommage à Jacques Cauvin.
- Ibáñez, J.J., Anderson, P.C., González-Urquijo, J., Gibaja, J., 2016. Cereal cultivation and domestication as shown by microtexture analysis of sickle gloss through confocal microscopy. *J. Archaeol. Sci.* 73, 62–81.
- Ibáñez, J.J., González-Urquijo, J.E., Gibaja, J., 2014. Discriminating wild vs domestic cereal harvesting micropolish through laser confocal microscopy. *J. Archaeol. Sci.* 48, 96–103.
- Ibáñez, J.J., Lazun, T., González-Urquijo, J., 2019. Identifying experimental tool use through confocal microscopy. *J. Archaeol. Method Theory* 26 (3), 1176–1215.
- Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., Jäger, F., 2014. Projectile impact fractures and launching mechanisms: Results of a controlled ballistic experiment using replica Levallois points. *J. Archaeol. Sci.* 48, 73–83.
- Jensen, H.J., 1986. Unretouched blades in the late mesolithic of south scandinavia. A functional study. *Oxford J. Archeol.* 5 (1), 19–33.
- Jones, P.R., 1980. Experimental butchery with modern stone tools and its relevance for Palaeolithic archaeology. *World Archaeol.* 12 (2), 153–165.
- Kaufman, D., 1995. Microburins and Microliths of the Levantine Epipalaeolithic: A Comment on the Paper by Neeley and Barton. *Antiquity* 69, 375–381.
- Keeley, L., 1980. *Experimental Determination of Stone Tool Uses: A Microwear Analysis*. The University of Chicago Press, Chicago.
- Keller, C.M., 1966. The development of edge damage patterns on stone tools. *Man* 1 (4), 501–511. <https://doi.org/10.2307/2798343>.
- Key, A., Fisch, M.R., Eren, M.I., 2018. Early stage blunting causes rapid reductions in stone tool performance. *J. Archaeol. Sci.* 91, 1–11.
- Key, A.J.M., 2016. Integrating mechanical and ergonomic research within functional and morphological analyses of lithic cutting technology: Key principles and future experimental directions. *Ethnoarchaeology* 8 (1), 69–89.
- Key, A.J.M., Lycett, S.J., 2015. Edge angle as a variably influential factor in flake cutting efficiency: An experimental investigation of its relationship with tool size and loading: Edge angle as a factor in flake cutting efficiency. *Archaeometry* 57 (5), 911–927.
- Key, A.J.M., Proffitt, T., Stefani, E., Lycett, S.J., 2016. Looking at handaxes from another angle: Assessing the ergonomic and functional importance of edge form in Acheulean bifaces. *J. Anthropol. Archaeol.* 44, 43–55.
- Key, A.J.M., Stemp, W.J., Morozov, M., Proffitt, T., de la Torre, I., 2015. Is Loading a significantly influential factor in the development of lithic microwear? An experimental test using LSCM on basalt from olduvai gorge. *J. Archaeol. Method Theory* 22 (4), 1193–1214.
- Kimball, L.R., Allen, P.E., Kimball, J.F., Schlichting, B., Pham, K., 1998. The Analysis of Microwear Polishes with the Atomic Force Microscope XIII Congress of the International Union of Prehistoric and Protohistoric Sciences. ABACO, Forlì, Italy, pp. 1121–1132.
- Kimball, L.R., Coffey, T.S., Faulks, N.R., Dellinger, S.E., Karas, N.M., Hidjati, N., 2017. A Multi-instrument Study of Microwear Polishes on Mousterian Tools from Weasel Cave (Myshtylagty Lagat), Russia. *Lithic Technol.* 42 (2–3), 61–76.
- Kimball, L.R., Kimball, J.F., Allen, P.E., 1995. Microwear polishes as viewed through the atomic force microscope: New frontiers. *Lithic Technol.* 20, 6–28.
- Lewenstein, S., 1991. Edge angles and tool function among the Maya: a meaningful relationship? In: Hester, T.R., Shafer, H. (Eds.), *Maya Stone Tools: Selected Papers from the Second Maya Lithic Conference*. Prehistory Press, Madison, pp. 207–217.
- Linton, J., Monna, F., Sestier, C., Martineau, R., 2016. Quantifying cereal-reaping microwear on flint tools: An experimental approach: Quantifying cereal-reaping microwear on flint tools. *Archaeometry* 58 (6), 1038–1046.
- Macdonald, D.A., 2013. *Interpreting Variability Through Multiple Methodologies: The Integration of Form and Function in Epipalaeolithic Microliths*. University of Toronto, Department of Anthropology.
- Macdonald, D.A., 2014. The application of focus variation microscopy for lithic use-wear quantification. *J. Archaeol. Sci.* 48, 26–33.
- Macdonald, D.A., Harman, R., Evans, A., 2018. Replicating surface texture: Preliminary testing of molding compound accuracy for surface measurements. *J. Archaeol. Sci.: Reports* 18, 839–846.
- Macdonald, D.A., Xie, L., Gallo, T., 2019. Here's the dirt: First applications of confocal microscopy for quantifying microwear on experimental ground stone earth working tools. *J. Archaeol. Sci.: Reports* 26, 101861. <https://doi.org/10.1016/j.jasrep.2019.05.026>.
- Maher, L.A., Richter, T., Stock, J.T., 2012. The pre-Natufian Epipalaeolithic: Long term behavioural trends in the Levant. *Evol. Anthropol.* 21, 69–81.
- Maleki, I., Wolski, M., Woloszynski, T., Podsiadło, P., Stachowiak, G., 2019. A comparison of multiscale surface curvature characterization methods for tribological surfaces. *Tribol. Online* 14 (1), 8–17.
- Marder, O., Pelegri, J., Valentin, B., Valla, F., 2006. Reconstructing Microlith Shaping: Archaeological and experimental observations of early and final natufian lunates at Eynan (Ain Mallaha) Israel. *Eurasian Prehistory* 4, 99–158.
- McCall, G.S., 2005. An experimental examination of the potential function of Early Stone Age technology and implications for subsistence behavior. *Lithic Technol.* 30, 29–43.
- McGrath, K., El-Zaatari, S., Guatelli-Steinberg, D., Stanton, M.A., Reid, D.J., Stoinski, T.S., Cranfield, M.R., Mudakikwa, A., McFarlin, S.C., 2018. Quantifying linear enamel hypoplasia in Virunga Mountain gorillas and other great apes. *Am. J. Phys. Anthropol.* 166 (2), 337–352.
- Nadel, D., Danin, A., Power, R.C., Rosen, A.M., Bocquentin, F., Tsatskin, A., Rosenberg, D., Yeshurun, R., Weissbrod, L., Rebollo, N.R., Barzilai, O., Boaretto, E., 2013. Earliest floral grave lining from 13,700–11,700-year-old Natufian burials at Raqefet Cave, Mt. Carmel, Israel. *Proc. Natl. Acad. Sci.* 110 (29), 11774–11778.
- Neeley, M., Barton, C.M., 1994. A New Approach to Interpreting Late Pleistocene Microlith Industries in Southeast Asia. *Antiquity* 68, 275–288.
- Noy, T., 1991. Art and Decoration of the Natufian at Nahal Oren. In: Bar-Yosef, O., Valla, F. (Eds.), *The Natufian Culture in the Levant*. International Monographs in Prehistory, Michigan, pp. 557–568.
- Odell, G., 1981. The morphological express at the function junction: Searching for meaning in lithic tool types. *J. Anthropol. Res.* 37, 319–342.
- Olśzewski, D., 2001. My “Back and Truncated Bladelet”, Your “Point”: Terminology and Interpretation in Levantine Epipalaeolithic Assemblages. In: Canerva, I., Lemorini, C., Zampette, D., Biagi, P. (Eds.), *Beyond Tools: Redefining the PPN Lithic Assemblages of the Levant*. Proceedings of the Third Workshop on PPN Chipped Lithic Industries. Ex Oriente, Berlin, pp. 303–318.
- Olśzewski, D., 2006. Issues in the Levantine Epipalaeolithic: The Madamaghan, Nebekian and Qalkhan (Levant Epipalaeolithic). *Paléorient* 32, 19–26.
- Olśzewski, D., 2011. Lithic “Culture” Issues: Insights from the Wadi al-Hasa Epipalaeolithic. In: Healey, E., Campbell, S., Maeda, O. (Eds.), *The State of the Stone: Terminologies, Continuities and Contexts in Near Eastern Lithics*. ex Oriente, Berlin, pp. 51–66.
- Pfleging, J., Iovita, R., Buchli, J., 2019. Influence of force and duration on stone tool wear: results from experiments with a force-controlled robot. *Archaeol. Anthropol. Sci.* 11, 5921–5935. <https://doi.org/10.1007/s12520-018-0729-0>.
- Ragni, A.J., Teaford, M.F., Ungar, P.S., 2017. A molar microwear texture analysis of pitheciid primates. *Am. J. Primatol.* 79 (12), e22697. <https://doi.org/10.1002/ajp.22697>.
- Richter, T., 2007. A Comparative Use-Wear Analysis of late Epipalaeolithic (Natufian) chipped stone artefacts from the southern Levant. *Levant* 39 (1), 97–122.
- Robertson, G., Aattenbrow, V., Hiscock, P., 2009. Multiple uses for Australian backed artifacts. *Antiquity* 83, 296–308.
- Schousboe, R., 1977. Microscopic edge structures and microfractures on obsidian. *Lithic Technol.* 6, 14–21.
- Siegel, P.E., 1985. Edge angle analysis as a functional indicator: A test. *Lithic Technol.* 14, 90–94.
- Sonnenfeld, J., 1962. Interpreting the function of primitive implements. *Am. Antiq.* 28 (1), 56–65.
- Stemp, W.J., 2014. A review of quantification of lithic use-wear using profilometry: A methods based on metrology and fractal analysis. *J. Archaeol. Sci.* 48, 15–25.

- Stemp, W.J., n.d. On the importance of expedient stone tool use among the ancient Maya: tool size, edge angle, raw material, and use-wear, Keene State College, New Hampshire.
- Stemp, W.J., Andruskiewicz, M.D., Gleason, M.A., Rashid, Y.H., 2015a. Experiments in ancient Maya bloodletting: Quantification of surface wear on obsidian blades. *Archaeol. Anthropol. Sci.* 7 (4), 423–439.
- Stemp, W.J., Childs, B.E., Vionnet, S., 2010. Laser profilometry and length-scale analysis of stone tools: Second series experiment results. *Scanning* 32, 233–243.
- Stemp, W.J., Childs, B.E., Vionnet, S., Brown, C.A., 2009. Quantification and discrimination of lithic use-wear: surface profile measurements and length-scale fractal analysis. *Archaeometry* 51 (3), 366–382.
- Stemp, W.J., Chung, S., 2011. Discrimination of surface wear on obsidian tools using LSCM and ReLA: pilot study results (area-scale analysis of obsidian tool surfaces). *Scanning* 33, 279–293.
- Stemp, W.J., Lerner, H.J., Kristant, E.H., 2013. Quantifying Microwear on Experimental Mistassini Quartzite Scrapers: Preliminary Results of Exploratory Research Using LSCM and Scale-Sensitive Fractal Analysis: Quantifying microwear on experimental Mistassini quartzite scrapers. *SCA* 35 (1), 28–39.
- Stemp, W.J., Lerner, H.J., Kristant, E.H., 2018. Testing area-scale fractal complexity (Asfc) and laser scanning confocal microscopy (LSCM) to document and discriminate microwear on experimental quartzite scrapers: Documenting and discriminating microwear on quartzite scrapers. *Archaeometry* 60 (4), 660–677.
- Stemp, W.J., Macdonald, D.A., Gleason, M.A., 2019. Testing imaging confocal microscopy, laser scanning confocal microscopy, and focus variation microscopy for microscale measurement of edge cross-sections and calculation of edge curvature on stone tools: Preliminary results. *J. Archaeol. Sci.: Reports* 24, 513–525.
- Stemp, W.J., Stemp, M., 2001. UBM laser profilometry and lithic use-wear analysis: A variable length scale investigation of surface topography. *J. Archaeol. Sci.* 28 (1), 81–88.
- Stemp, W.J., Morozov, M., Key, A.J.M., 2015b. Quantifying lithic microwear with load variation on experimental basalt flakes using LSCM and area-scale fractal complexity (Asfc). *Surf. Topogr.: Metrol. Prop.* 3 (3), 034006. <https://doi.org/10.1088/2051-672X/3/3/034006>.
- Stemp, W.J., Stemp, M., 2003. Documenting stages of polish development on experimental stone tools: surface characterization by fractal geometry using UBM laser profilometry. *J. Archaeol. Sci.* 30 (3), 287–296. <https://linkinghub.elsevier.com/retrieve/pii/S030544030290837X>.
- Stemp, W.J., Watson, A.S., Evans, A.A., 2016. Surface analysis of stone and bone tools. *Surf. Topogr. Metrol. Prop.* 4, 1. <https://doi.org/10.1088/2051-672X/4/1/013001>. <https://iopscience.iop.org/article/10.1088/2051-672X/4/1/013001>.
- Strathern, M., 1969. Stone axes and flake tools: Evaluations from two New Guinea Highland Societies. *Proc. Prehist. Soc.* 35, 311–329.
- Tringham, R., Cooper, G., Odell, G., Voytek, B., Whitman, A., 1974. Experimentation in the formation of edge damage: a new approach to lithic analysis. *J. Field Archaeol.* 1 (1–2), 171–196.
- Ungar, P.S., Berger, L.R., 2018. Brief communication: Dental microwear and diet of Homo naledi. *Am. J. Phys. Anthropol.* 166 (1), 228–235.
- Unger-Hamilton, R., 1989. The Epi-Palaeolithic Southern Levant and the Origins of Cultivation. *Curr. Anthropol.* 30 (1), 88–103.
- Unger-Hamilton, R., 1991. Natufian Plant Husbandry in the Southern Levant and Comparison with that of the Neolithic Periods: The Lithic Perspective. In: Bar-Yosef, O., Valla, F. (Eds.), *The Natufian Culture in the Levant. International Monographs in Prehistory*, Michigan, pp. 483–520.
- Valla, F., Bar-Yosef, O., 2013. Natufian Foragers in the Levant. *International Monographs in Prehistory*, Ann Arbor, Michigan.
- Valla, F., Le Mort, F., Plisson, H., 1991. Les Fouilles en Cours sur la Terrasse d'Hayonim. In: Bar-Yosef, O., Valla, F. (Eds.), *The Natufian Culture in the Levant. International Monographs in Prehistory*, Oxford, pp. 93–110.
- Valletta, F., Smilansky, U., Goring-Morris, A.N., Grosman, L., 2020. On measuring the mean edge angle of lithic tools based on 3-D models – A case study from the southern Levantine Epipalaeolithic. *Archaeol. Anthropol. Sci.* 12 (2). <https://doi.org/10.1007/s12520-019-00954-w>.
- Vardi, J., Golan, A., Levy, D., Gilead, I., 2010. Tracing sickle blade levels of wear and discard patterns: A new sickle gloss quantification method. *J. Archaeol. Sci.* 37 (7), 1716–1724.
- Vargiolu, R., Morero, E., Boleti, A., Procopiou, H., Pailler-Mattei, C., Zahouani, H., 2007. Effect of abrasion during stone tool vase drilling in Bronze Age Crete. *Wear* 263, 48–56.
- Vaughan, P., 1981. Lithic Microwear Experimentation and the Functional Analysis of a Lower Magdalenian Stone Tool Assemblage. University of Pennsylvania, Ann Arbor.
- Vaughan, P., 1985. Use-wear Analysis of Flaked Stone Tools. The University of Arizona Press, Tucson.
- Werner, J.J., 2018. An experimental investigation of the effects of post-depositional damage on current quantitative use-wear methods. *J. Archaeol. Sci.: Reports* 17, 597–604.
- White, J.P., 1967. Ethno-archaeology in New Guinea: Two examples. *Mankind* 6, 409–414.
- White, J.P., Thomas, D.H., 1972. What Mean These Stones? Ethnotaxonomic Models and Archaeological Interpretations in the New Guinea Highlands. In: Clarke, D.L. (Ed.), *Models in Archaeology*. Methuen, London, pp. 275–308.
- Wilmsen, E.N., 1968. Functional analysis of flaked stone artifacts. *Am. Antiq.* 33 (2), 156–161.
- Yamada, S., 2000. Development of the Neolithic: Lithic Use-wear Analysis of Major Tool Types in Southern Levant. Harvard University, Cambridge, Department of Anthropology.