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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

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ABSTRACT

The application of micro- and nanotechnology, adopted from engineering and materials sciences, is proving valuable in studying stone tool surfaces. Measurement systems for surface characterization have been coupled with parameters that allow for the mathematical characterization of stone tool surfaces. For this project, a Sensofar S neox imaging confocal microscope (ICM)/focus variation microscope (FVM) and an Olympus LEXT OLS4100 laser scanning confocal microscope (LSCM) are used to mathematically document the edge cross-sections on five chipped stone tools made from basalt, chert, obsidian, and quartz. Based on the surface documentation of edge cross-sections, a new algorithm for the calculation of edge curvature at multiple scales is tested. Results indicate the confocal systems experience difficulty documenting edge cross-sections. However, focus variation microscopy can mathematically document edge cross-sections on stone tools made from basalt and chert, thus permitting the calculation of edge curvature over multiple scales of measurement. Microscale documentation of edge cross-sections and calculation of edge curvature will be helpful in understanding the relationships between tool edges, edge sharpness, edge attrition, and microwear. Comparisons between these three measurement systems (ICM, LSCM, FVM) provide information necessary for further method development in edge cross-section measurement and the potential to generate more robust edge analysis protocols.

1. Introduction

The application of engineering technologies and metrological/tribological techniques to understand the microstructures of stone and bone tool surfaces has rapidly increased over the last decade or so (Stemp et al., 2016). Particular foci for research have centered on microwear analysis and the mechanisms of wear formation on stone tools. Overwhelmingly, it is the flat surfaces of stone tools that have been quantitatively documented on the microscale using various microscopes and mathematical parameters; however, little attention has been paid to the apex where two stone tool surfaces converge (henceforth, edge cross-section). This location has been variously referred to by a number of terms, but, generally, the term “edge angle” has been most commonly used when discussing stone tool edge apices or cross-sectional shapes on the macroscale. These edges, where the two lithic surfaces meet at the margin, are the locations that are most often used - whether it is for cutting, scraping, or piercing tasks. Tool cross-sectional shape can influence how a tool functioned, the types of tasks it performed, as well as the potential for post-depositional breakage. Thus, tool cross-sectional shape is an integral attribute for understanding how stone tools functioned in prehistory. However, obtaining measurements of edge angles is notoriously challenging (see Dibble and Bernard, 1980). Furthermore, standard methods of cross-section edge angle measurements (goniometer, calipers, edge molding, etc.) record the angle at the macroscale without considering differences in microscale texture that can affect tool function and influence wear formation.

In this first attempt to document the edge cross-sections on five stone tools made from basalt, chert, obsidian, and quartz, we utilize two different microscopes that provide three different surface measurement systems. To mathematically characterize these stone tool surfaces, we used a Sensofar S neox imaging confocal microscope (ICM)/focus variation microscope (FVM) and an Olympus LEXT OLS4100 laser scanning confocal microscope (LSCM). The edge cross-section measurements of these different tools were calculated at various scales using a

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scale-sensitive parameter known as edge curvature, which is based on Heron's formula. Comparisons between these three measurement systems provide information necessary for method development in edge cross-section documentation and mathematical characterization, as well as the calculation of edge curvature at various scales. A number of important observations were made with respect to tool edge angles, lithic raw material properties, and the ability to successfully document the experimental tools' edge cross-sections using edge curvature at different measurement scales.

2. Stone tool characteristics and properties

2.1. Form-function

Since the inception of chipped stone tool functional analysis, archaeologists have, in one way or another, attempted to assess how a tool was used based on its morphology. In the mid- to late nineteenth and early twentieth centuries, the way to understand form-function relationships of stone tools relied heavily on the "speculative functional approach" (Stemp et al., 2016). Some archaeologists realized the potential value of ethnographic analogy and compared their excavated lithic artifacts to the stone tools used by indigenous peoples. Despite the potential value of ethnographic analogy, most assessments of tool use continued to rely on tool form and were biased by Western techno-cultural interpretations based on modern technology and historic metal tools (Olausson 1980, p 48–49; Vaughan 1981, p 6–10; Vaughan 1985, p 3). Some methods to infer stone tool use considered tool form prior to attempting very basic "actualistic" studies (Vaughan, 1981; Vaughan 1985, p 4). One approach focused on direct verification, in which "… the researcher conduct[ed] only such tests as [were] thought necessary to support or disprove a given hypothesis about the function(s) of a certain class of implement, with the major emphasis being placed on comparison of experimental and prehistoric use-wear patterns" (Vaughan 1981, p 14). Another approach, an efficiency study, was "… designed only to demonstrate whether or not a copy of a prehistoric tool, or an original example, [was] capable of efficiently executing the hypothesized task" (Vaughan 1981, p 14).

Over time, archaeologists continued to rely on form-function relationships and comparisons to modern tools with limited examination of stone tools for traces of use-related wear using magnification (Stemp et al. 2016 p 2; Vaughan 1981, pp. 15–27). The publication of the English translation of Semenov's (1964) volume on microwear analysis significantly changed how stone tool function was approached. The form of the tool was still considered by archaeologists when interpreting how it was used, but microwear traces and eventually residues on stone tools became more significant methods for the interpretation of stone tool function (see Odell 1981, 2004, pp. 135–173; van Gijn 1989, pp. 143–144).

2.2. Edge angle

More significant connections between tool design and function included the importance of the tool edge. Early interest in edge angle can be seen in Sonnenfeld's (1962) work on edge tapering on stone celts and Keller's (1966) measurement of edge cross-sections with progressive tool use. Notably, Wilmsen's (1968) article on edge angle and tool function was influential in suggesting a connection between acute angles and longitudinal motion activities, like cutting, and wider or more obtuse edges angle with transverse motion activities, like scraping, or the working of harder materials. Ethnoarchaeological work also revealed that tool form may be less important in terms of determining or predicting function than the characteristics of a tool's edge (Gould et al., 1971; White, 1967; White and Thomas, 1972), although general tool size and how well it could be gripped were important variables considered by indigenous people from New Guinea and Australia (also see Key, 2016; Key and Lycett, 2015; Key et al., 2016 for grip, pressure, and ergonomics). Archaeologists increasingly incorporated measures of edge angles, in addition to other variables, in their analyses of stone tool function and sometimes included use-wear analysis techniques as well (e.g., Borel et al., 2013; Broadbent and Knutsson, 1975; Collins, 2008; Eren, 2013; Eren and Lycett, 2016; Hurcombe, 1992; Iovita, 2014; Jensen, 1986; Jones, 1980; Keeley, 1980; Key and Lycett, 2015; Key et al., 2016; Kononenko, 2011; McCall, 2005; Schousboe, 1977; Siegel, 1985; Tringham et al., 1974; Vaughan, 1981, 1985). There is a certain logic to these functional associations, but they are neither exclusive nor always predictive of tool motion type, as has been demonstrated by use-wear analysts (e.g., Odell, 1981; Lewenstein, 1991) and the fact that stone tools have often been demonstrated to be multi-functional based on ethnographic observations (Strathern, 1969; White, 1967). Nevertheless, Key et al. (2018, p 8) demonstrate in their experiments that edge angle has a significant effect on cutting performance at the earliest stages of tool use with wider tool edges associated with greater force, material displacement and work requirements. However, they suspect that edge angle has a more limited effect in cutting later in tool use as edges become increasingly blunt and less effective, thus requiring more force.

One consideration for microwear analysts is the scale of data documentation for comparing edge angle and wear. Use of conventional measurement equipment, such as a goniometer (Keeley 1980, p 19; see Dibble and Bernard, 1980), cannot mathematically document the small-scale topographical features of a tool edge. It may be that more modern two- or three-dimensional morphometric analyses of stone tool edges may assist in addressing issues related to edge angle, edge length, and edge shape (e.g., Davis et al., 2015; Eren and Lycett, 2016; Lycett and von Cramon-Taubadel, 2013; Shipton et al., 2016). Combining morphometrics with microwear analysis is one approach that could provide some microscale data of tool edges (see Borel et al., 2013, 2017; Chacón et al., 2016).

2.3. Edge sharpness

In engineering and forensic science, much work has been done to measure tool sharpness and the effects of sharpness on tool use on various substances (e.g. Atkins, 2009; Boisly et al., 2016; Leonov and Badiaev, 2016; McCarthy et al., 2007, 2010; McGorry et al., 2003; Reilly et al., 2004; Reyssat et al., 2012; Schuldt et al., 2013, 2016; Shergold and Fleck, 2004; Stępień, 2010; Tsai et al., 2012). In recent years, a definition of sharpness has been honed down to a mathematical description of the roundedness of a tool edge at its tip or apex (point of intersection of the implement's two edges), which can be calculated using the tip or apex radius (see McCarthy et al., 2007, 2010). However, comparatively little attention has been paid, either directly or indirectly, to the importance of edge sharpness on lithic tools by archaeologists (e.g., Braun et al., 2008; Dewbury and Russell, 2007; Jones, 1980; Key, 2016; Key et al., 2018). This is no doubt because the cutting ability of an edge has traditionally been difficult to document and various methods have been proposed to mathematically measure cutting in terms of sharpness (McCarthy et al., 2007, 2010; McGorry et al., 2003; Reyssat et al., 2012; Schuldt et al., 2013, 2016). On lithic implements, sharpness has been even more difficult to document quantitatively given the irregularity of stone tool edges, and often sharpness has been subsumed under discussions of edge angle (e.g., Castronuevo, 2009; Key, 2016; Lemorini et al., 2015). As such, frequently both qualitative and quantitative descriptions of cut-mark cross-section shapes and/or the microfeatures within cutmarks have been used to infer metal or stone tool edge angles/shapes, as potential proxies for sharpness (e.g., Bello and Soligo, 2008; Fisher Jr., 1995; Krasinski, 2018; L'homme, 2007; West and Louys, 2007). It should be noted that more recently the mathematical documentation of cutmarks using various morphometric, photogrammetry, and other mathematical or statistical techniques has produced favorable results in distinguishing those made by metal and different types of stone tools (e.g., Bello and Soligo, 2008; Maté-González et al., 2016, 2018; Otárola-Castillo et al., 2018; Palomeque González et al., 2017; Yravedra et al., 2015, 2017), but distinguishing between cutmarks and post-depositional striations still poses problems (Monnier and Bischoff, 2014). These techniques might prove useful as measures of tool sharpness based on the dimensions and morphologies of the cut marks, but more work is needed.

Despite these difficulties, archaeologists and other scientists are aware that tool edge sharpness is connected to many other variables in terms of successful tool use, including tool edge morphology, edge attrition, tool efficiency, force/load required to use the tool, use-duration, wear, and tool resharpening, among others (see Ackerly, 1978; Braun et al., 2008; Claudon and Marsot, 2006; Key, 2016; Key and Lycett, 2015; Key et al., 2018; McCarthy et al., 2007; McCarthy et al., 2010; McGorry et al., 2003; Rech et al., 2018; Schuldt et al., 2013; Shergold and Fleck, 2004; Stępień, 2010; also see Pfleging et al., 2018). Edge sharpness is also correlated with raw material types. For example, Buck (1982, p 266) reports that fresh obsidian flake-tool edges measure roughly 30 Å or 3 nm in thickness and are extremely sharp, but the edges are delicate and highly susceptible to microfracturing due to use or post-depositional forces. Concerns about raw materials, edge types, and the recognition of the characteristics of cut marks on bone have also been recently voiced (see Dominguez-Rodrigo et al., 2017; Monnier and Bischoff, 2014; Yravedra et al., 2017).

2.4. Raw material variation

Much has been written about the role of lithic raw materials in microwear development and the analysis of stone tool surfaces on the microscale. There is widespread acknowledgment among microwear analysts that different stone types do not develop use-related wear at the same rates, that the characteristics associated with wear on different stone types are not the same, and that some microscopic techniques will be less successful for microwear analysis given the differences in the physical and chemical properties of the stone type from which a tool is made (e.g., Bradley and Clayton, 1987; Hurcombe, 1997; Keeley, 1980; Knutsson, 1988; Ollé et al., 2016; Pedergnana and Ollé, 2016). This has also been documented through experimental research in the quantification of surface roughness/texture on stone tools and testing of lithic raw material properties in terms of wear accrual (e.g., Benito-Calvo et al., 2018; Clemente Conte and Gibaja Bao, 2009; Key et al., 2015; Lerner, 2007, 2014; Lerner et al., 2007, 2010; Stemp and Chung, 2011; Stemp and Stemp, 2001; Stemp et al., 2013, 2015a, 2015b, 2016, 2018). Differences in lithic raw material physical and chemical composition no doubt play a role in the quantification of edge cross-sections of stone tools on the microscale as well, but this has not been tested using surface metrology until now.

3. Quantification of stone tool surfaces and microwear

Early attempts by archaeologists to quantify stone tool surface structure and microwear using some kind of scientific method generally provided poor results. In part, this was due to the available technology of the time, as well as difficulties in applying engineering-based analysis protocols to stone tools (Bauch, 1984–1986; Beyries et al., 1988; Dumont, 1982; Grace et al., 1985; Keeley, 1980; Rees et al., 1991). More successful work in quantification of microwear began with a series of research projects that relied on very different techniques and better surface measurement systems and algorithms than previously employed (Anderson et al., 1998; Kimball et al., 1995, 1998; Stemp and Stemp, 2001, 2003; Tomenchuk, 1985; Vargiolu et al., 2003). In many ways, the results of these projects generated more interest and confidence in the potential development of methods to quantify microwear on stone tools. In the last 10–15 years, archaeologists have employed a range of different technologies and surface analysis data to mathematically document the surfaces of stone tools on micro- and nanoscales. Notably, measurement systems that have been used to mathematically document stone tool surfaces include atomic force microscopy (Faulks et al., 2011; Kimball et al., 2017), interferometry (Anderson et al., 2006; Kimball et al., 2017), laser profilometry (Stemp et al., 2009, 2010; Stemp, 2014), laser scanning confocal microscopy (Evans and Donahue, 2008, Evans and Macdonald, 2011; Macdonald et al., 2018; Stemp and Chung, 2011; Stemp et al., 2013, 2015a, 2015b; Stevens et al., 2010; Evans et al., 2014; Werner, 2018), and focus variation microscopy (Evans and Macdonald, 2011; Macdonald, 2014; Pfleging et al., 2018). In addition to the methods described above, quantification of stone tool surfaces has also been done using external or independent data acquisition/analytical techniques in conjunction with various forms of microscopy, such as image analysis and geographic information systems (GIS) (e.g., Benito-Calvo et al., 2015, 2018; González-Urquijo and Ibáñez-Estévez, 2003; Lerner, 2007, 2014; Lerner et al., 2010).

3.1. Scale-sensitive fractal analysis

Interest in and application of algorithms to document the surface roughness on stone tools have grown by leaps and bounds (see Stemp et al., 2016). This is partly due to the realization that interdisciplinary study of lithic surfaces could allow rigorous and reliable development of and access to extremely sophisticated surface measurement systems and surface measurement parameters. In particular, the mathematical description and documentation of irregular surfaces at multiple scales is extremely valuable for studying a variety of materials (e.g., bone, metal, stone, tooth) of interest to archaeologists. Notably, scale-sensitive fractal analysis has been successfully used to document the worn and unworn surfaces on various types of stone tools and lithic raw materials at different scales (e.g., Key et al., 2015; Pfleging et al., 2018; Stemp and Chung, 2011; Stemp et al., 2013, 2015a, 2015b, 2018; Stemp and Stemp, 2001, 2003).

4. Experimental tools

For this first experiment testing LSCM, ICM, and FVM with the edge curvature parameter, five tools made from different raw materials were selected (Fig. 1). They included a hard-hammer percussion flake made from Olduvai Gorge basalt (Tanzania), a hard-hammer percussion flake

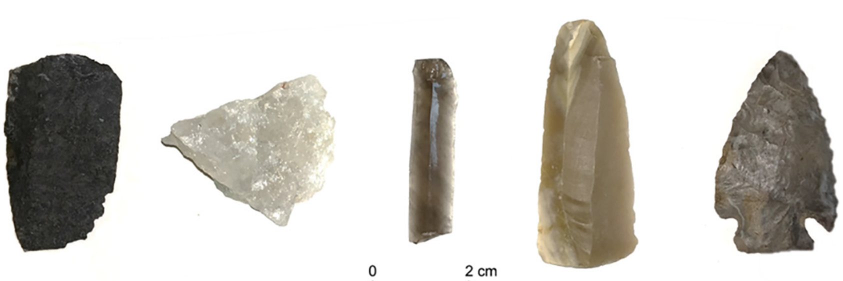


Fig. 1. The stone tools (from left to right) – basalt flake, quartz flake, obsidian blade segment, chert blade segment, and chert corner-notched biface.

made from Olduvai Gorge quartz, a pressure blade segment made from El Chayal obsidian (Guatemala), an indirect percussion blade segment made from NBCZ chert (Belize), and a corner-notched biface made from Onondaga chert (Canada). The quartz and basalt flakes are experimental tools, while the blade segments and small biface are artifacts. Prior to documenting the stone tools with the three microscopy methods, the edge angles of the tools were measured with a goniometer. Each tool's edge was measured in four different locations where the area scans using LSCM, ICM, and FVM would be taken. The average edge angles based on the goniometer measurements were 38.1° [SD = 1.204] for the basalt flake, 40.8° [SD = 3.023] for the quartz flake, 26.4° [SD = 3.188] for the obsidian blade segment, 32.3° [SD = 1.822] for the chert blade segment, and 39.2° [SD = 3.651] for the chert corner-notched biface.

5. Methods

5.1. Equipment

For this pilot project, three different measurement systems were employed, specifically laser scanning confocal microscopy (LSCM) using an Olympus LEXT OLS4100, imaging confocal microscopy (ICM) using a Sensofar S neox, and focus variation microscopy (FVM) also using the Sensofar S neox. An advantage of the Olympus and Sensofar S neox microscopes is that they provide the ability to visually observe the surfaces being measured and they can generate two- and three-dimensional models of a measured surface based on mathematical documentation. The measurable surface models are calibrated to ISO standards, allowing for measurements of surface topography to the nanoscale. Descriptions of the operating systems for the two different microscopes are provided below.

5.1.1. Laser scanning confocal microscopy (LSCM)

To measure a surface, LSCM creates images using reflected laser light from a discrete focal plane. The Olympus LEXT OLS4100 laser scanning confocal microscope uses a microelectromechanical resonant galvano mirror to produce a 405 nm laser to measure a surface. The laser light is reflected back from the measured surface (i.e., the focal plane) through a pinhole aperture located in front of a photomultiplier (i.e., sensor), which records changes in surface elevation. The system generates measurement slices at specific elevations where the surface is in focus. The aforementioned slices of the surface are produced by an objective lens affixed to a motorized head, which moves the laser up and down in order to focus on surface points of variable vertical distances. The vertical distance of each focal slice is determined by both the diameter of the pinhole aperture and the wavelength of the laser light that is reflected back from the surface being measured (see Sheppard and Shotton, 1997). When all of the in-focus slices at different elevations are combined, a complete three-dimensional mathematical map of the measured area is generated. The specifications for the LEXT OLS4100 include a vertical scale (z-axis) resolution of 0.8 nm and a height display resolution of 1.0 nm. For this experiment, both the 20× [0.60 NA (numerical aperture)] and 50× [0.95 NA] objectives were used with the fine pitch setting. Based on published specifications, the Olympus LEXT OLS4100 should be capable of measuring acute-angled specimens with a slope up to 85° (www.olympus-ims.com). This would result in an edge angle of 10° at the apex of the two 85° sloped surfaces (Fig. 2).

5.1.2. Imaging confocal microscopy (ICM)

In addition to LSCM, images were also taken with ICM, specifically scanning microdisplay confocal microscopy. The model used for the acquisition was a Sensofar S neox microscope. Unlike laser scanning confocal microscopy, scanning microdisplay confocal microscopy uses the same illumination in the optical path to acquire a confocal and brightfield image. This allows for the observation of the object's surface in brightfield illumination to properly position the objective and identify the desired region of interest. Furthermore, it allows for the collection of a brightfield image while collecting confocal data. To acquire images, a light source is collimated (parallel rays to minimize spread) and directed towards a reflective microdisplay. Single pixels of the microdisplay are switched on individually, thus a single point of the surface is illuminated at a time. Each pixel of the microdisplay is imaged on the surface, which is recorded by a camera (Matilla et al., 2016). The specification for the Sensofar S neox is dependent on the objective used, and at the highest numerical aperture (NA) confocal data has a vertical resolution of 1.0 nm (using the 150× objective) and a maximum slope of up to 71° (www.sensofar.com), resulting in a cross-section edge angle of 38°.

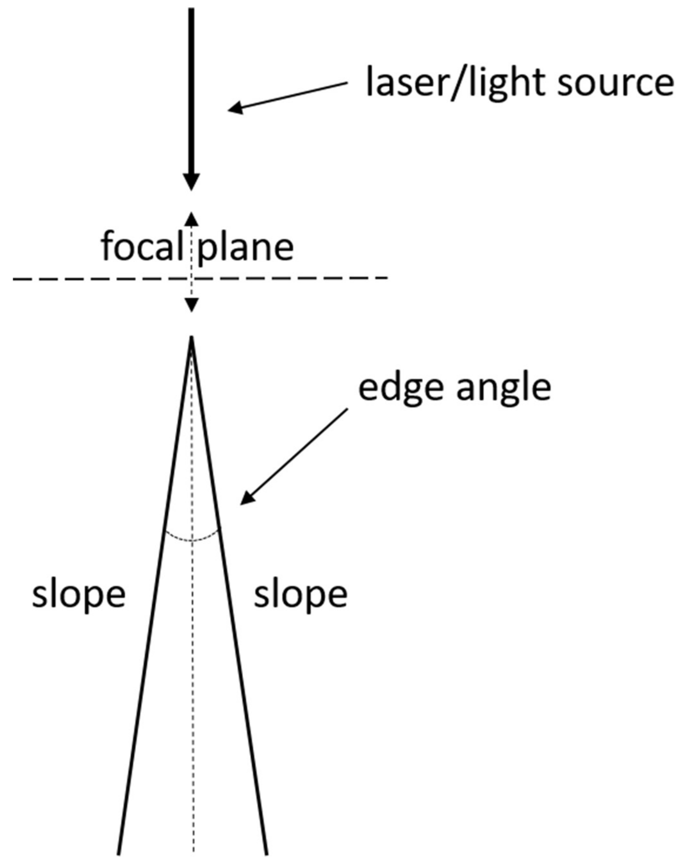


Fig. 2. Diagram of the slope and edge angle of a stone tool edge cross-section under a microscope objective.

5.1.3. Focus variation microscopy (FVM)

In addition to scanning microdisplay confocal microscopy, the Sensofar S neox also has a focus variation mode of data collection. To collect data, the microscope objectives are moved vertically in relation to the object, bringing the object in and out of focus. The sensor within the microscope identifies and measures in-focus pixels, building a completely in-focus image though the vertical scan. The sensor then evaluates the region around each pixel to calculate the standard deviation of the grey levels of the local region, thereby measuring the focus. Thus, the surface topography is calculated through the in-focus depth of each plane and a composite image is generated from the in-focus slices (Helmli, 2011). FVM is better at capturing data from rough surfaces and sharp edges than confocal microscopy. Based on the manufacturer's specifications, the focus variation mode on the Sensofar S neox can measure a surface to a maximum slope of 86°, which is roughly an 8° cross-section edge angle. For this study, the 50× objective [0.80 NA] was used for data collection.

5.2. Stone tool cleaning

Cleaning of the stone tools in this pilot project was minimal as we were more concerned with the ability of the different measurement systems to reliably document the tools' edge cross-sections and the calculation of edge curvature than with differences between specific quantification data of each of the tools' edges. After initial examination under a metallurgical microscope (Unitron MS-2BD) at 200× magnification, each of the tools was washed in a grit-free detergent in warm water and then rinsed in cold water and allowed to dry. The tools were then re-examined for any adhering dirt or residues. None were observed on the edges to be measured. Prior to documentation of the edges' microtopographies using the Olympus LEXT OLS4100 and the Sensofar S neox microscopes, the edges were cleaned one last time with alcohol wipes. In future analyses of stone tool edges a more rigorous cleaning protocol will be followed involving acidic and basic solution baths (see Macdonald and Evans, 2014; Stemp et al., 2009, 2013).

5.3. Stone tool edge measurement

For each tool, a total of 28 area scans were taken of the edge, including four area scan measurements using LSCM with the 20× objective, four using LSCM with the 50× objective, four using ICM with the 20× objective, four using ICM with the 50× objective, and four using FVM at 6× speed, four using FVM at 10× speed, and four using FVM at 14× speed (all with the 50× objective). The different speed rates for FVM represent the amount of individual data points collected; higher speeds result in faster data collection but lowered vertical and lateral resolution. The areas for measurement (x- and y-axis) were randomly selected across the cleaned cross-section edges of each of the tools. In all, 140 area scan measurements were taken on the five stone tools. The respective areas for a single scan documented using each approach are included in Table 1.

5.4. Calculation of edge curvature

The scale-sensitive fractal analysis parameters that have been most commonly used to document surface roughness on stone tools include relative length (RL), relative area (Srel) and area-scale fractal complexity (Asfc) (e.g., Key et al., 2015; Pfleging et al., 2018; Stemp, 2014; Stemp and Chung, 2011; Stemp et al., 2009, 2013, 2015a, 2015b, 2018). Like surface profiles and surface areas, curvatures naturally vary with scale (Brown et al. 2018, p 855). For this research, a newly developed scale-sensitive analysis parameter - edge curvature - was chosen to process the tip or apex measurement (i.e., edge cross-section) data acquired using the microscopes (Gleason et al., 2013, 2014; Vulliez et al., 2014; also see Bartkowiak and Brown, 2016, 2019; Bartkowiak et al., 2018 for areal multiscale curvature). Edge curvature (k_h) measures the geometry of a tip or apex of two convergent surfaces based on Heron's formula. This formula uses the inverse of the radius as a function of scale of observation of a profile (Fig. 3). It calculates curvature based on three height points that are equally separated from one another. It uses the height points to fit a triangle at different scales, where scale is determined by the horizontal distance between the two corner points at the base of the triangle (Z1, Z3). The top point (Z2) is placed at the middle distance between the two base points of the triangle. Calculation of edge curvature at different scales is based on the application of virtual triangles with different distances between the three points (Z1, Z2, Z3). The area of the circumscribed virtual triangle is used to calculate edge curvature of the profile at that scale – the virtual triangle decreases in area with decreasing scale. In this instance, edge curvature measurements were calculated using a hybrid of Heron's formula and the calculus derivative method because the edge angles on the stone tools were less than 90°. Profiles of a tool's edge generated using MountainsMap (2017) software were exported to Curvsoft (2017), which calculated the curvature of each edge at various scales. Relatedly, Brown et al. ((2018), p 855; see Bartkowiak and Brown, 2016, 2019) note that areal curvature can be employed to identify lay, or surface directionality (i.e., anisotropy), through the analysis of maximal and minimal curvature vector orientation. The identification of surface directionality in the calculation of curvature on stone tool edges could potentially be linked to determinations of motion type or angle of prehension, particularly in relation to unequal wear development across the tip or apex of a tool edge.

Table 1
Summary of microscope system specifications and measurement surface areas.

Microscope system - objective	Area – x-axis (μm) × y-axis (μm)
LSCM – 20× objective	643 × 643
LSCM – 50× objective	256 × 256
ICM – 20× objective	850 × 710
ICM – 50× objective	340 × 284
FVM – 50× objective	340 × 284

6. Results

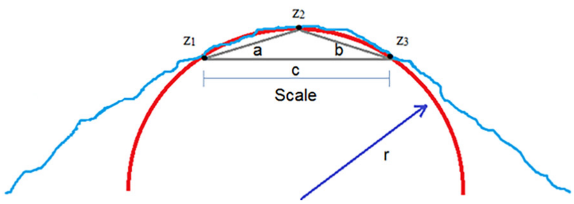
6.1. Edge cross-section measurement using LSCM, ICM, and FVM

None of the five tools' edge cross-sections could be reliably measured at the microscale with LSCM using the 20× objective or the 50× objective (Figs. 4 and 5). Too little of the surface microstructure was recorded by the laser. The surface microstructure that could not be reliably measured appears as 'spikes' in the area scan images. ICM also experienced difficulty measuring the edge cross-sections of the five stone tools using the 20× and 50× objectives (Figs. 6 and 7). The surface microstructure that could not be reliably measured using ICM appears as blank/colorless spaces in the area scan images. As discussed below, the edge angles of all of these the tools appeared to be too acute for the laser of the laser scanning confocal microscope and the scanning microdisplay of the imaging confocal microscope. Moreover, aspects of certain tools' material properties, including reflectivity, appeared to play a role as well.

In contrast to the two methods of confocal microscopy, FVM proved successful at mathematically documenting the surface microtopography of some of the tool edge cross-sections at different speeds (6×, 10×, 14×). Each speed provides advantages and disadvantages. Essentially, the faster speeds require less time to measure a surface, but the resolution (i.e., the detail of documented surface structure) is lower. In order to acquire the best resolution for the calculation of edge curvature, the 6× speed surface measurements were selected. Using this approach, documentation of surface microtopography of the tool edge cross-sections was possible for the basalt flake, the chert blade segment, and the chert corner-notched biface (Figs. 8–10 left). However, the edge cross-sections of the obsidian blade segment and the quartz flake could not be reliably measured using the FVM at any of the three speeds. Reasons for this are discussed below.

6.2. Edge curvature calculation

To calculate edge curvature (k_h) using the hybrid Heron's formula and the calculus derivative method in Curvsoft (2017), five profiles were selected in each of the four cross-sectional area scans for each of the three tools (the basalt flake, the chert blade segment, and the chert corner-notched biface) that were successfully measured using FVM for a total of 60 calculations (Figs. 8–10 right). From the profile data, edge curvatures were calculated at four different scales (5.0, 15.0, 25.0, 45.0 μm) (Figs. 11–13). For all five of the profiles in each of the four area scans for the three different tools, edge curvature could be calculated at these four scales. As expected, the edge curvature at the largest scale (45.0 μm) provided a surface that appeared "smoother". As the scale of calculation decreases, the surface across the edge is



$$s = \frac{a+b+c}{2}$$

$$h = \sqrt{s\,(s\,-a)\,(s\,-b)\,(s\,-c)}$$

$$k_h = \frac{1}{r} = \frac{4h}{a \cdot b \cdot c}$$

Fig. 3. Definition of profile points for curvature calculation adapted from Gleason et al. (2013).

documented in much finer detail and thus appears “rougher”. Given the good results of this first experiment, the determination of which scales of edge curvature provide the most valuable information for answering different questions related to edge cross-sections will need to be pursued in future replicative experiments. These controlled experiments will be critical in determining at which scales of calculation edge sharpness, edge attrition, and microwear can be best documented and discriminated before application to lithic artifacts is possible. Issues concerning the effects of post-depositional damage on calculation of edge curvature on stone tools will also need to be studied before attempting to quantify edge curvature at multiple scales on stone tools from the archaeological record.

7. Discussion

The results of this first attempt to mathematically document stone tool edge cross-sections and calculate edge curvature demonstrate both successes and failures. Importantly, for stone tools made from certain raw materials using specific microscope systems, it is possible to reliably measure edge cross-sections on the microscale and to calculate edge curvature at multiple scales using the hybrid version of Heron's formula. Based on current experimental results, only FVM was able to document the microtopography of the tool edge cross-sections such that sufficient surface data were generated for the calculation of edge curvature over multiple scales. Moreover, only those tools made from basalt and chert could be reliably measured to generate the necessary data. What these basalt and chert tools have in common appears to be a certain degree of surface roughness, the lack of high surface reflectivity, and overall edge angles that were wide enough for measurement using FVM. Consequently, the future documentation of stone tool edges for the purposes of analyzing edge sharpness, edge attrition, and microwear is possible under these conditions.

Of significant value is the information regarding why some tool edge cross-sections could not be measured using LSCM, ICM, and FVM. For edge cross-section measurements, edge angle matters, regardless of the lithic raw material from which the tools were made. If edge angle is too acute, the laser or light of the confocal microscopes that document a surface does not sufficiently reflect back to the sensor and the converging surfaces of the tool cannot be mathematically documented (see Zhou, 2014). This same issue was noted by Mueller et al. (2016, p 83–84): “… the slope of the specimen surface affects the measurement accuracy in confocal microscopy. The light intensity decreases at the detector when the surface slope increases. Therefore, the signal-to-noise ratio will be lower for surface regions which have high slopes”. Despite the slope specifications provided by the confocal microscopes' manufacturers, we observed that surface slopes greater than ~70° [edge angles less than ~40°] caused difficulty in measuring stone tool edges for the two confocal microscopes. This also presented some difficulties for the FVM, particularly for the obsidian blade segment. For LSCM, ICM, and FVM, the obsidian blade segment was also difficult to measure

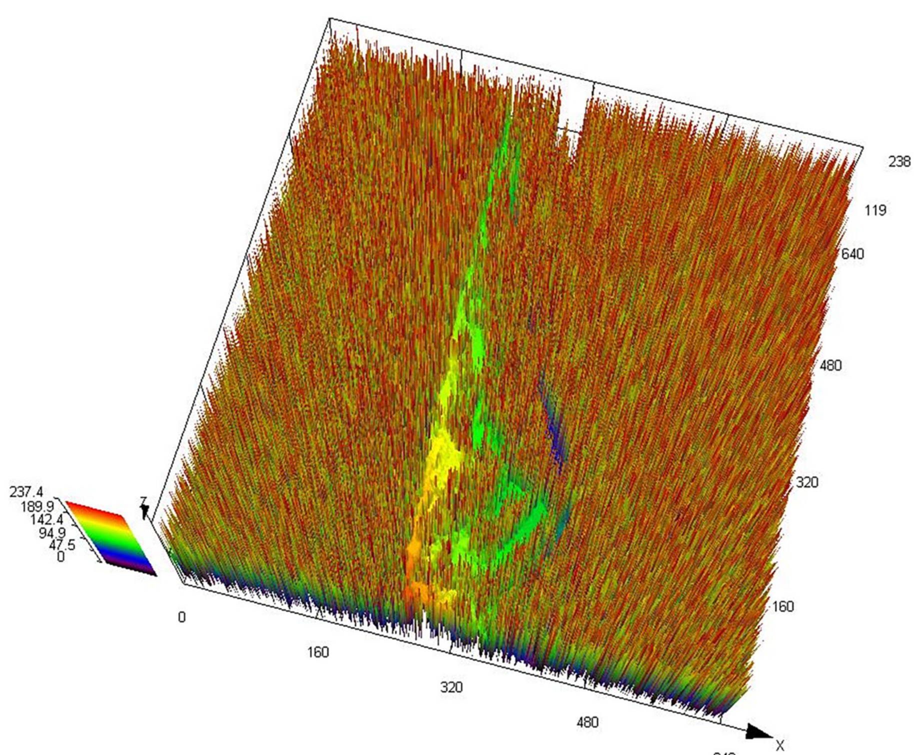


Fig. 4. Area scan #3 of the obsidian blade segment edge using LSCM with the 20× objective. The ‘spikes’ [low signal-to-noise ratio] indicate locations where no surface data could be measured on the edge cross-section.

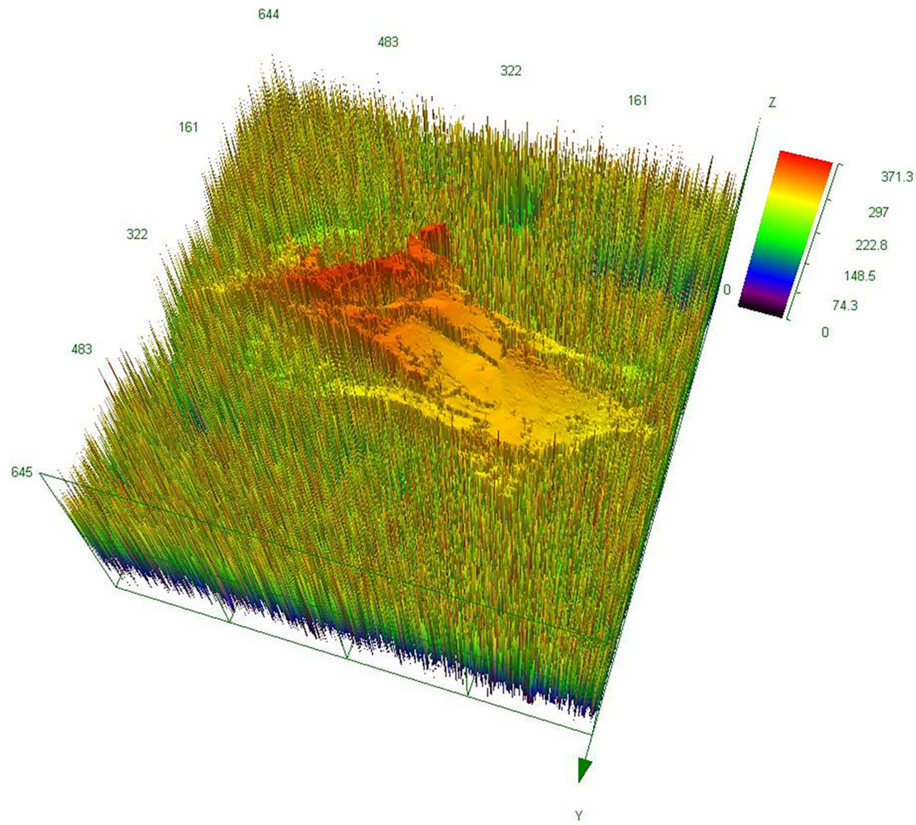


Fig. 5. Area scan #1 of the quartz flake edge using LSCM with the 20× objective. The 'spikes' [low signal-to-noise ratio] indicate locations where no surface data could be measured on the edge cross-section.

because the edge cross-section was trapezoidal in shape with one surface oriented at a 90° angle (i.e., completely parallel) to the axis of the laser or light source.

Different lithic raw materials also affected the ability to document the tool edge cross-sections. In this experiment, basalt and chert tool edges could be reliably documented using FVM. As noted, the fact that these tools' surfaces are not very reflective and they possessed a certain degree of surface roughness seems to have played a role. For the obsidian blade segment, it appears that the very smooth surface texture of the material and its high reflectivity, in combination with the acutely angled edge, caused a substantial amount of the laser and light of the confocal microscopes to be reflected away from the sensors. Mueller et al. (2016, p 93) also noted that the intensity of the detector/sensor on the confocal microscope was affected by the reflectivity of the specimen surface in their work. For the quartz flake, both the high reflectivity of the tool surface and the fact that it is composed of quartz crystal facets

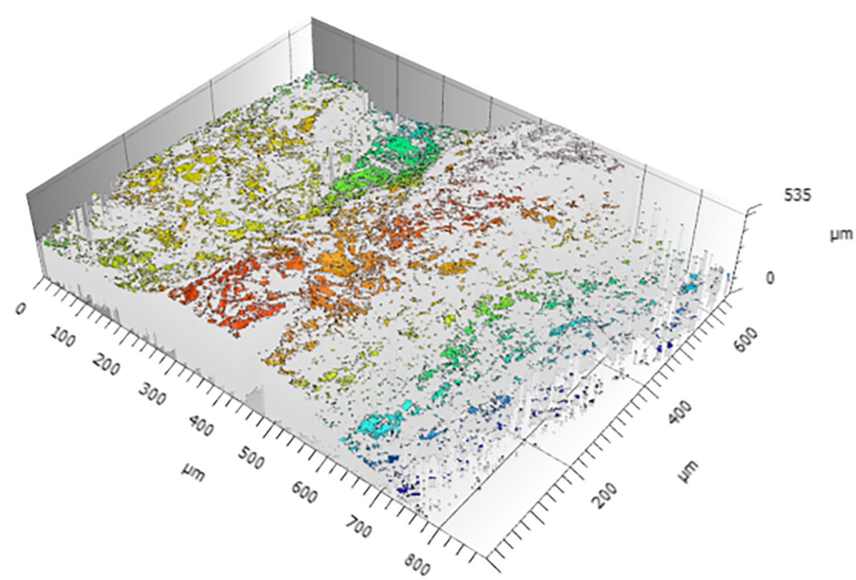


Fig. 6. Area scan #2 of the chert blade segment using ICM with the 20× objective. The empty spaces indicate locations where no surface data could be measured on the edge cross-section.

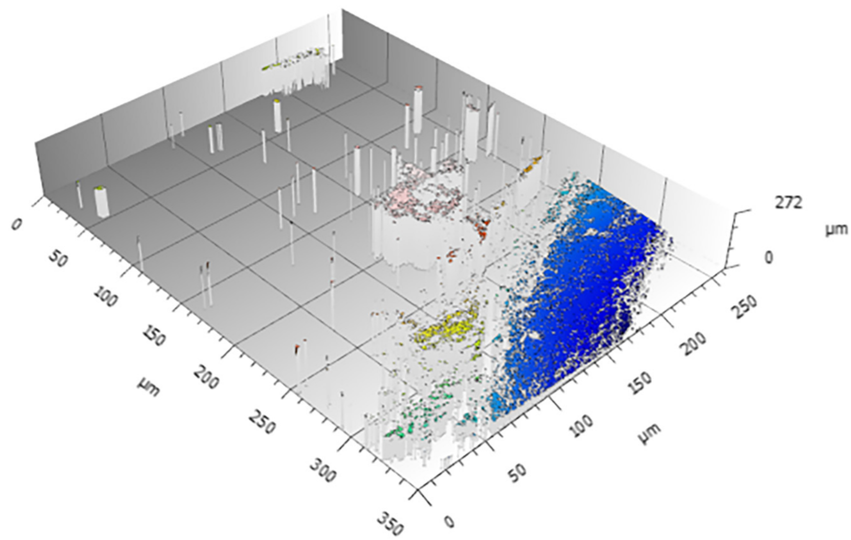


Fig. 7. Area scan #4 of the chert blade segment using ICM with the 50× objective. The empty spaces indicate locations where no surface data could be measured on the edge cross-section.

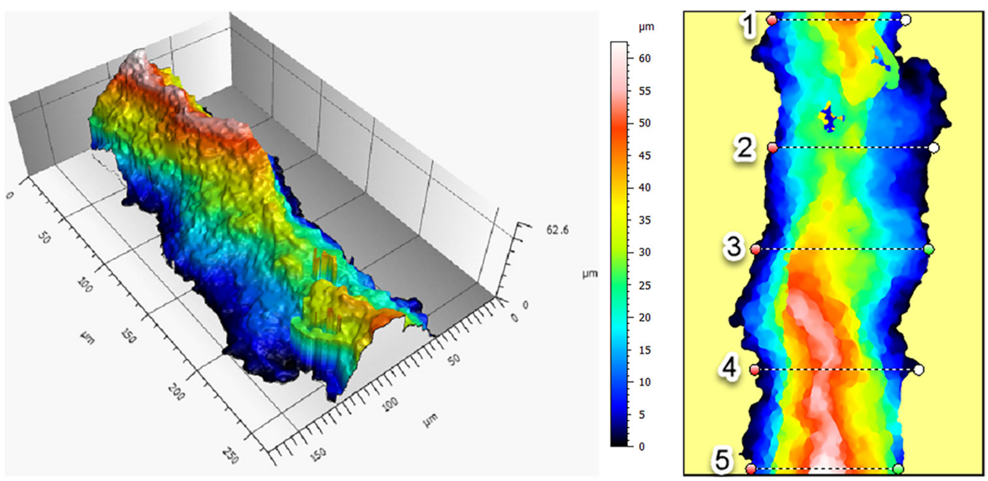


Fig. 8. Area scan #4 of the basalt flake using FVM with the 50× objective at 6× speed (left); location of the five profiles used to calculate edge curvature (right).

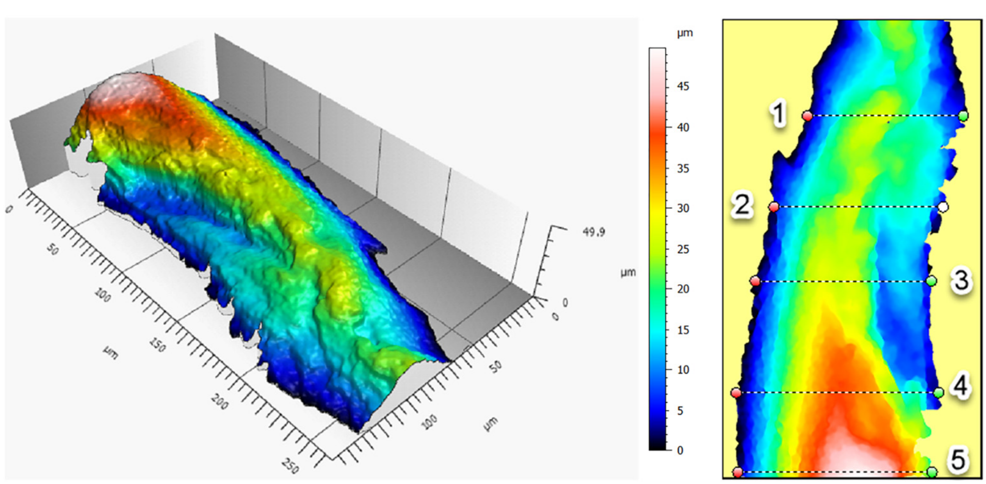


Fig. 9. Area scan #1 of the chert blade segment using FVM with the 50× objective at 6× speed (left); location of the five profiles used to calculate edge curvature (right).

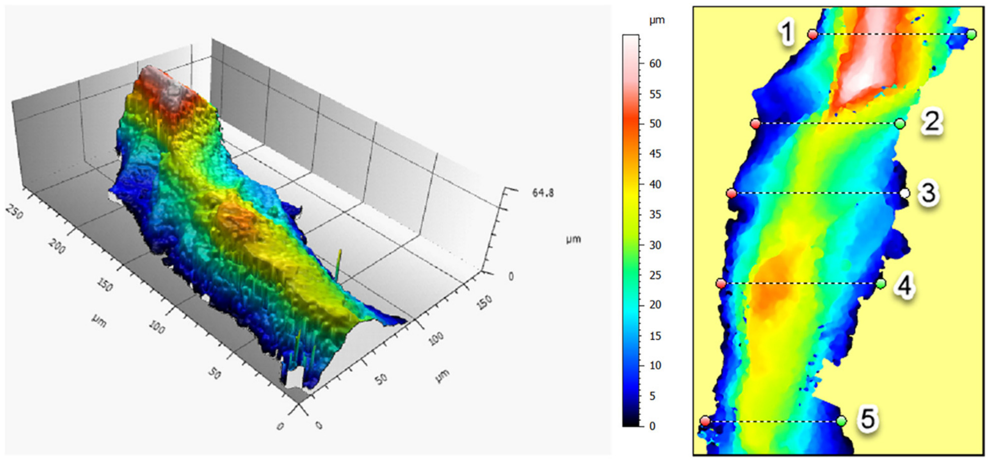


Fig. 10. Area scan #1 of the chert corner-notched biface using FVM with the 50× objective at 6× speed (left); location of the five profiles used to calculate edge curvature (right).

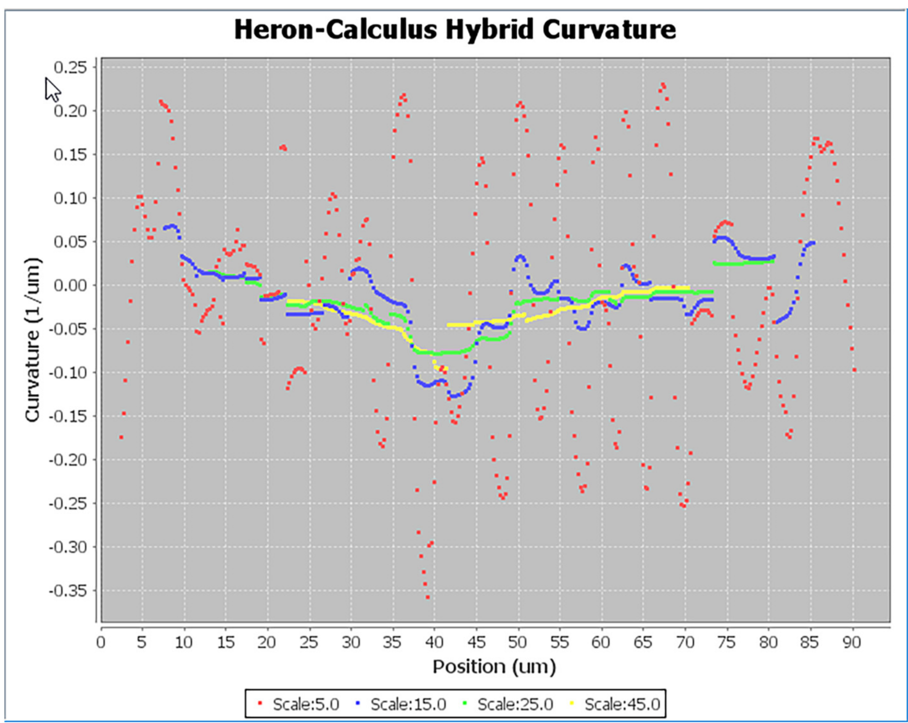


Fig. 11. Edge curvature calculated for profile #4 of area scan #4 on the basalt flake edge at multiple scales.

whose smooth surfaces are oriented in many different directions scattered much of the laser and light away from the confocal microscopes' sensors. Problems were also noted when trying to document the edge cross-sections of the obsidian blade and the quartz flake using FVM. In particular, it was not possible to get proper illumination of the edge of the quartz flake for the optimal resolution necessary for FVM because of the incident (through the objective) light source. As with LSCM and ICM, the quartz flake's multidirectional crystal facet orientation scattered significant amounts of light away from the sensor.

Despite these difficulties, some measurement and lighting solutions are proposed. The use of a ring-light with FVM would likely assist with measuring obsidian and quartz. A ring light is affixed around the microscope objective and provides 360° illumination of the sample rather than the incident light that is projected through the objective. This allows light from many different directions to bounce off the tools' sloped reflective surfaces at multiple angles, ensuring that more light bounces back to the sensor. A solution to measuring very acute edge angles using confocal microscopes might be to take several measurements of the same tool edge at various angles relative to the optical axis of the objective lens. These measurements from different angles could then be stitched together to create a complete model of the tool's edge (see Mueller et al., 2016, p 94). Stitching like this could be used for other methods of surface documentation, such as image analysis and GIS.

For the preliminary experiment presented here, edge curvature was calculated for five individual profiles of the tool edge cross-sections. In future work, additional profiles can be used to generate multi-scalar edge curvature data. With the edge curvature calculated at multiple scales using more profiles, determining which scales are the most significant for comparing tool edges would then be more reliable.

8. Conclusion

The results of this first experiment indicate that edge curvature can

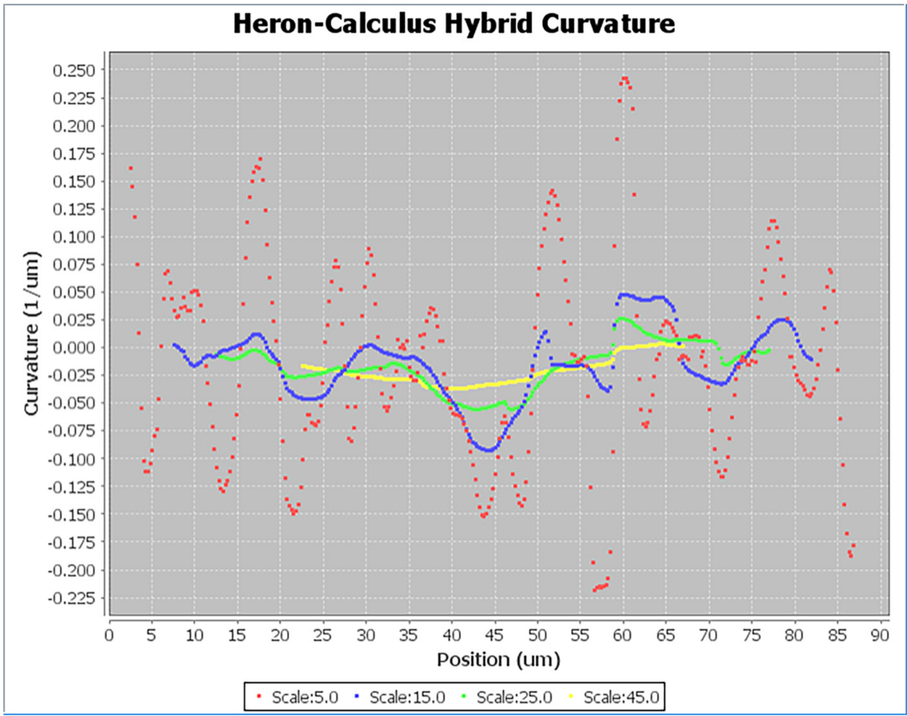


Fig. 12. Edge curvature calculated for profile #1 of area scan #1 on the chert blade segment edge at multiple scales.

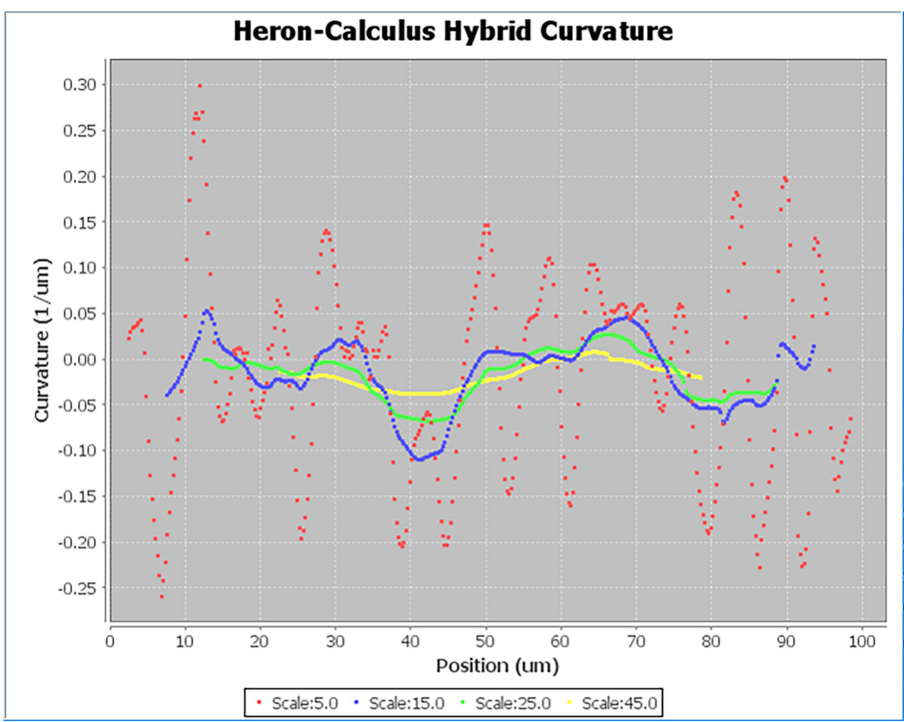


Fig. 13. Edge curvature calculated for profile #3 of area scan #1 on the chert corner-notched biface edge at multiple scales.

be calculated at multiple scales on stone tools. This provides another possible avenue for lithic analysts to mathematically document, describe, and discriminate stone tool edges. However, more experiments are needed to determine the repeatability of this approach and to address some of the problems identified with the confocal microscopes and the documentation of very acute edges, as well as tools made from obsidian and quartz. Minimally, using FVM with the hybrid version of Heron's formula allows for calculation of edge curvature on basalt and chert tools with edge angles greater than roughly 32°.

With further refinement of the technique, involving experiments with more tools and the adjustment of the testing protocols based on recommendations noted above, it is believed edge curvature will contribute substantial information about the changes in edge form and microsurface structure that can be applied to questions of edge sharpness, edge attrition, and microwear on experimental and archaeological stone tools. It is also possible that changes in surface roughness along the edges could be used in functional analyses that incorporate tool use-duration and variations in the application of load, among other variables. However, before transitioning to the analysis of lithic artifacts, understanding how post-deposition (Werner, 2018) on stone tool edges will affect quantification of edge cross-sections and calculations of edge curvature will need to be explored.

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