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ORIGINAL PAPER

Quantifying use-wear traces through RIMAPS and Variogram analyses

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Abstract The aim of this paper is to present the results obtained through the application of two imaging methods named rotated image with maximum average power spectrum (RIMAPS) and Variograms to mathematically characterize distinct patterns of worked materials on used edges of lithic artifacts. Both analytical procedures were performed on digitized images taken with an electronic microscope, allowing for the quantitative description of a given surface and revealing its topographic patterns. The preliminary research conducted on a sample of experimental lithic artifacts used to process different materials has shown promising results to the extent that fingerprints of different work processes (hide, bone, and wood-working) can be drawn.

Keywords Use-wear · RIMAPS · Variograms · Lithic technology · Quantification

Introduction

The purpose of this paper is to introduce a new method to quantify microwear traces on lithic artifacts in order

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to identify their context of use. The study of the tool use is an important mean to elucidate the social dynamic developed by past societies to the extent that people introduced artifacts into contexts they wanted to change (Ingold 1993; Wobst 2000). It is well known that much of the diversity in tool design appears to be related to the tasks for which the lithic instruments were intended and used for (see for example, Bamforth 1986; Binford 1979; Nelson and Lippmeier 1993; Shott 1986).

Currently, use-wear methodology is a consolidated and powerful approach to determine the activities and resources exploited by past societies (Anderson-Gerfaud 1986; Keeley 1980; Lemorini et al. 2006; Mansur-Franchomme 1983; van Gijn 2008). This method makes explicit the linkage between the stone technology and other spheres of resource processing, vastly contributing to our overall understanding of social organization.

Controlled experimental research carried out by many archaeologists has proved that microwear traces left by different worked materials are indeed distinctive and they could be distinguished using an incident light microscope (Keeley 1980; Mansur-Franchomme 1983; Semenov 1964). The observation through optical microscopy has been strongly supported by chemical studies showing that the micropolish layer contains residues of worked materials (Anderson-Gerfaud 1986; Evans and Donahue 2005; Jahren et al. 1997; Mansur-Franchomme 1983).

Nevertheless, one of the main critiques that this method has received is related to the qualitative character of the criteria employed to infer the function of a stone tool. The use-wear features mainly rely on visual aspects described according to their brightness, smoothness, and microtopographic characteristics (Keeley 1980). From the beginning of the 1980s, several attempts have been made to quantify micropolishes with different levels of success (Beyries et al. 1988; Dumont 1982; Grace 1989; Grace et al. 1985; Keeley 1980; Knutsson 1988).

During the last decades, the research effort towards an accurate and deep understanding of use-wear formation processes, along with the need to overcome the problems in the employment of qualitative criteria for microtrace description, have considerably grown. Thus, different methods of use-wear quantification have been improved. Most of these studies have focused on two micropolish features: (a) its texture measurable through the intensity of reflected light (e.g., Barceló et al. 2001; González Urquijo and Ibañez Estévez 2003; Mansur and Srhenisky 1996; Vila and Gallart 1993) and (b) its topography, quantifying the roughness of the used surface using different optical devices (e.g., Evans and Donahue 2008; Kimball et al. 1995; Stemp and Stemp 2001, 2003; Stemp et al. 2009). Also, by means of an image analysis technique, Lerner (2007) quantified invasiveness of edge modification and invasiveness of use-related wear as function of raw material variability, showing the significance of the latter in determining rates of wear accrual.

Despite the differences between these approaches, all of them showed that surface roughness and texture of lithic tools vary according to the worked material and that these differences could be measured using different mathematical models.

In order to achieve a more accurate description of use-wear traces, new imaging techniques are reported: rotated image with maximum average power spectrum (RIMAPS) and Variograms. RIMAPS is a surface characterization technique that uses digitized images from a surface under study to detect the main directions that represent the typical topographic pattern present on the surface. The Variogram method allows quantification of the topographic features of a surface, specially the typical length scales. These techniques have been successfully applied to the study of metals, sediments, and plants (Favret and Fuentes 2003; Fuentes and Faybishenko 2004) overcoming issues related to the illuminations used to observe the specimens or the crystalline structure of the lithic raw material.

The objectives of this paper are: (a) to give support to the visual variables that are commonly used in use-wear studies, (b) to elucidate if the visual details observed have correlates measurable through topographic patterns, (c) to evaluate the robustness and applicability range of the RIMAPS and Variogram techniques in the analysis and characterization of lithic surfaces.

RIMAPS and Variograms

RIMAPS technique

RIMAPS is a new imaging characterization technique independent of the class of microscopy and the conditions used for observation as long as these remain constant (Favret and Fuentes 2003, 2004; Favret et al. 2006, 2008; Fuentes and Favret 2002).

This technique consists basically of two steps: in first place, the image is rotated and secondly, for each angle of rotation the integral of one of the space variables of the two-dimensional Fourier transform is computed for each value of the other space variable using available commercial software (Elliot and Rao 1982; Felinger 1998; González-Velasco 1996; Gorcester et al. 1989; Jeffrey 2001; Mc Donough and Whalen 1995; Ozaktas et al. 1999; Palm 2003; Palmblad and Bergquist 2003; Smith 2002; Takeda 2000).

The mathematical procedure is essentially the rotation of the digitized image I(x, y) to a certain angle α and the calculation of the x-step of the two-dimensional Fourier

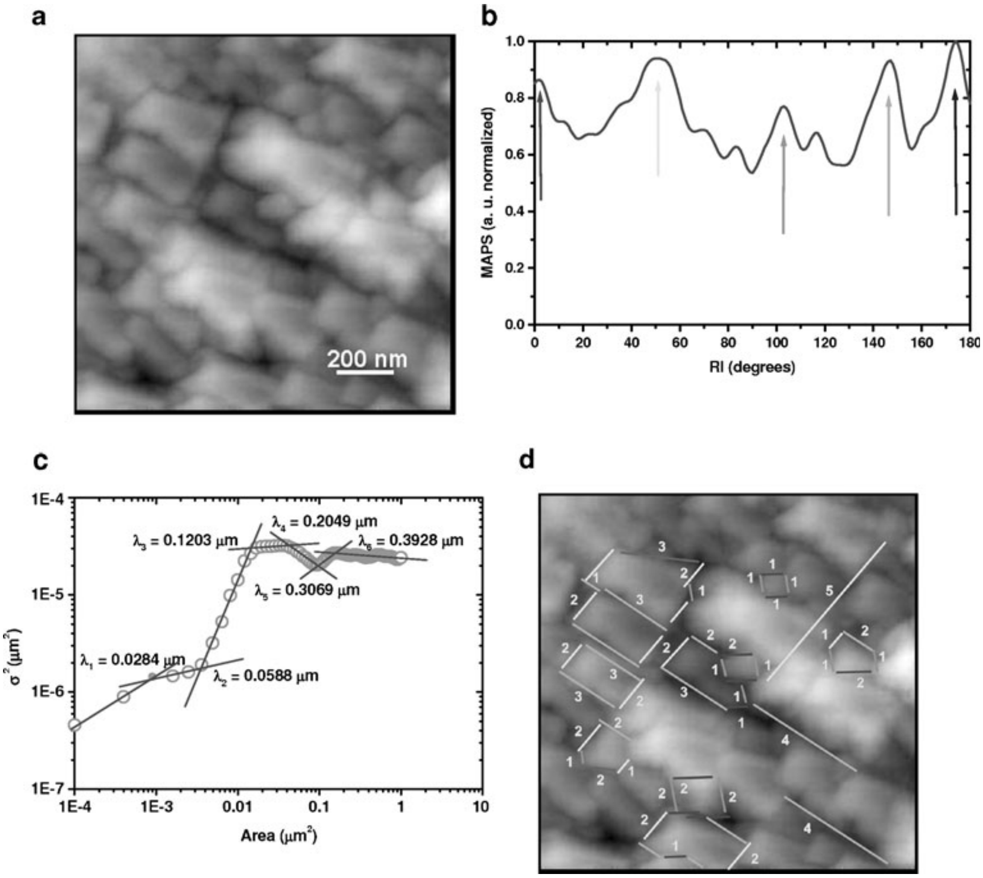

Fig. 1 RIMAPS and Variograms of a surface after deposition of CdTe **a** SPM image; **b** Representation of RIMAPS results. *Arrows* indicate the main directions of the topographic pattern; **c** Variogram results showing the length scales detected on surface; **d** *Lines* are superimposed to the SPM image to represent the directions detected by RIMAPS. The *numbers* appearing on the image represent the order of the cut-off length given by Variogram

transform for each y-line of the new image I_α (x, y) obtained after rotation:

$$I_\alpha(v_x, y) = \int_{-\infty}^{\infty} I_\alpha(x, y) \exp(-iv_x x)\ dx \quad , \qquad (1)$$

Results from Eq. 1 are averaged over all y-coordinate of the image and an average power spectrum (APS) is obtained for each angular position:

$$\mathrm{A}_\alpha(v_x) = |< I_\alpha(v_x, y)>^* < I_\alpha(v_x, y) >| \quad , \qquad (2)$$

where < > means average value and with $< |_\alpha(v_x, y)>^*$ being the complex conjugate of $< |_\alpha(v_x, y) >$. If the set of maximum values, in arbitrary units (a. u.), of all Average Power Spectra (MAPS)

$$\mathrm{M}(\alpha) = \max \mathrm{A}_\alpha(v_x) \qquad (3)$$

is plotted as a function of the angle of rotation (typically steps of 1°) of original image (RI), valuable information can be obtained from the surface pattern under study (Favret and Fuentes 2003; Fuentes and Favret 2002). The peaks appearing in the resulting plots indicate surface pattern orientation and its characteristic topographic form. As the RIMAPS spectra show symmetry after a full rotation of 360°, it is a common practice to present only the first 180° in the graphs. In the present paper, we focus our attention on both the tendencies of the curve and the intensity and shape of the peaks. To clarify the use of this technique, an example of experimental surface patterns and its complementary use with Variograms is given.

Variogram analysis

The Variogram method is based on a log–log representation of a characteristic roughness parameter versus the observation area of the digitized image. This algorithm is applicable

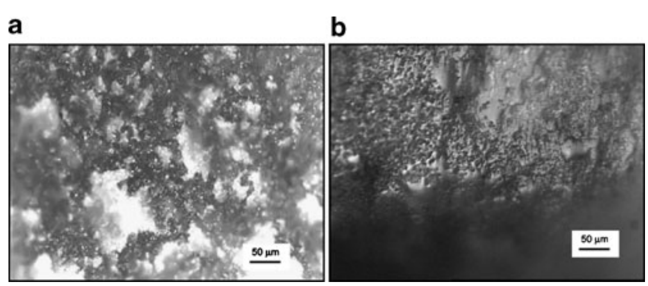

Fig. 2 LM images of two different lithic tools. It can be observed the problems of focusing and depth of field that make of this type of images a not adequate tool for obtaining quantitative results. **a** Non-worked lithic tool. **b** Lithic tool with wear traces of wood

to fractal and non-fractal surface characterization. It is well known that the geometric structure of rough surfaces is random, and that roughness features are found at a large number of length scales between the length of the sample and atomic scales. To understand the topography-dependent phenomena, the surface geometry must be described by parameters which take into account different length scales.

The root mean square average, σ, is one of the parameters most often used to characterize the surface roughness from a profile measured along this surface. While such parameters are useful for many applications, they do not cover information on the range of length scales over which different topographic features exist. Indeed, conventional parameters depend only on a few particular length scales, such as the instrument resolution or the sample length, while rough surfaces contain roughness at a large number of length scales.

During the last decade, various methods based on fractal analysis have been proposed to characterize surface roughness at different length scales. Most of the methods are aimed at calculating fractal parameters, in order to characterize the roughness at several length scales. For this purpose, the log–log representation of the variance σ^2 versus the sample size is used to determine the fractal dimension

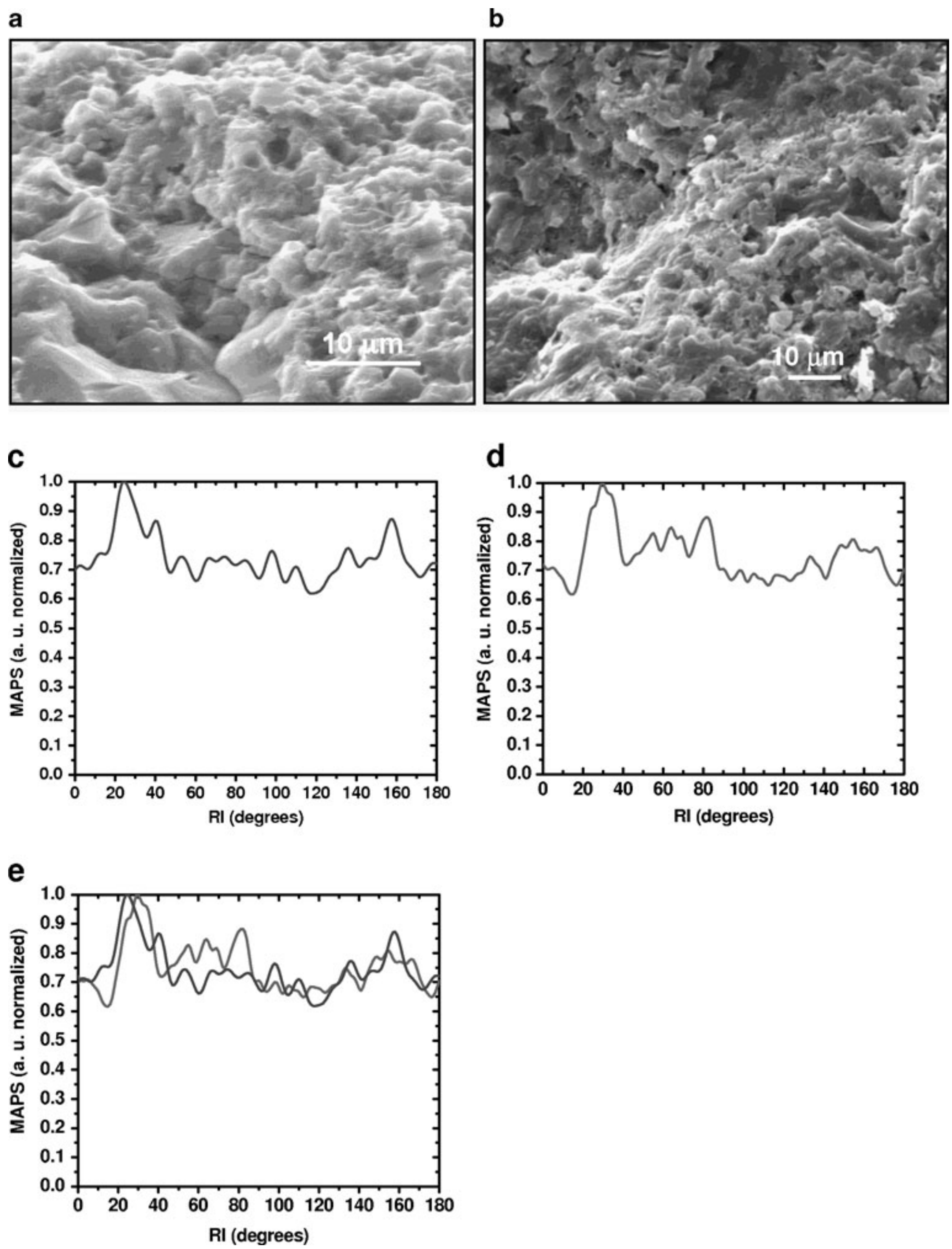

Fig. 3 RIMAPS results of unworked surfaces analysis. **a** and **b** are SEM micrographs of two different surfaces of lithic tools that have not been worked. **c** RIMAPS spectrum of first image. **d** RIMAPS spectrum of second image. **e** Comparison of spectra **c** and **d** showing a good matching between the two analyses. RIMAPS detects in both cases the same lithic tool characteristics on unworked surfaces corresponding to the same type of rock used as a tool

from the slope of the resulting curve (Babadagli and Develi 2003; Favret et al. 2004, 2006; Fuentes and Favret 2006; Fuentes and Faybishenko 2004; Williams and Beebe 1993). However, not all surfaces show fractal behavior. In these cases, the surface topography may not be appropriately described using a fractal dimension.

Therefore, we propose a new method for the quantification of length scale-dependent topography. From a given set of observation windows of different sizes of one digitized image, the variance parameter is calculated for different window areas on a surface. The calculated roughness parameter is then represented on a log–log plot as function of the window area. Intersections of different slopes in the plot give crossover lengths that characterize the surface.

Combined use of RIMAPS and Variograms

Combined use of the RIMAPS technique and the Variogram method is introduced in the example given in Fig. 1a. Simple glass plate with optical coating of CdTe was used to obtain an image with a scanning probe microscope (SPM). It can be seen from this example that RIMAPS allows finding the main directions existing on the surface topography and describing it by simple geometrical figures (Fig. 1b, d). The Variogram method gives the typical lengths that characterize the surface under study and that may be associated with the sizes of the simple shapes that represent the topographic pattern (Fig. 1c, d).

In particular, the analyses of different non-retouched flakes are presented in this paper to show the robustness of

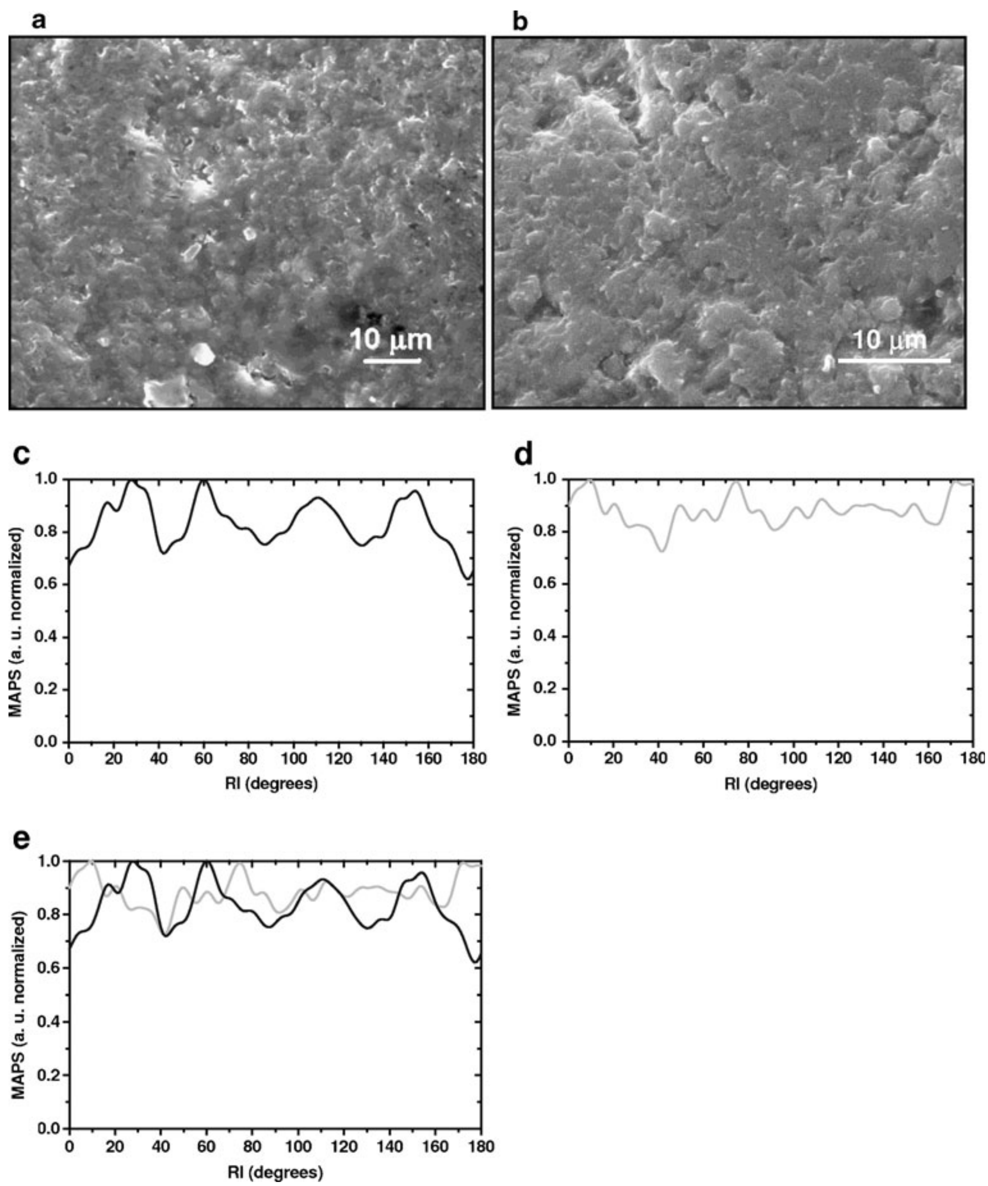

Fig. 4 RIMAPS results of the analysis of rhyolite surfaces used on hide. **a** and **b** SEM micrographs of two different surfaces of lithic tools with hide wear traces. **c** RIMAPS spectrum of first image. **d** RIMAPS spectrum of second image. **e** Comparison of spectra **c** and **d** showing the same general form of four rounded blocks of peaks. RIMAPS detects the surface with more work done when the four blocks appear well-defined

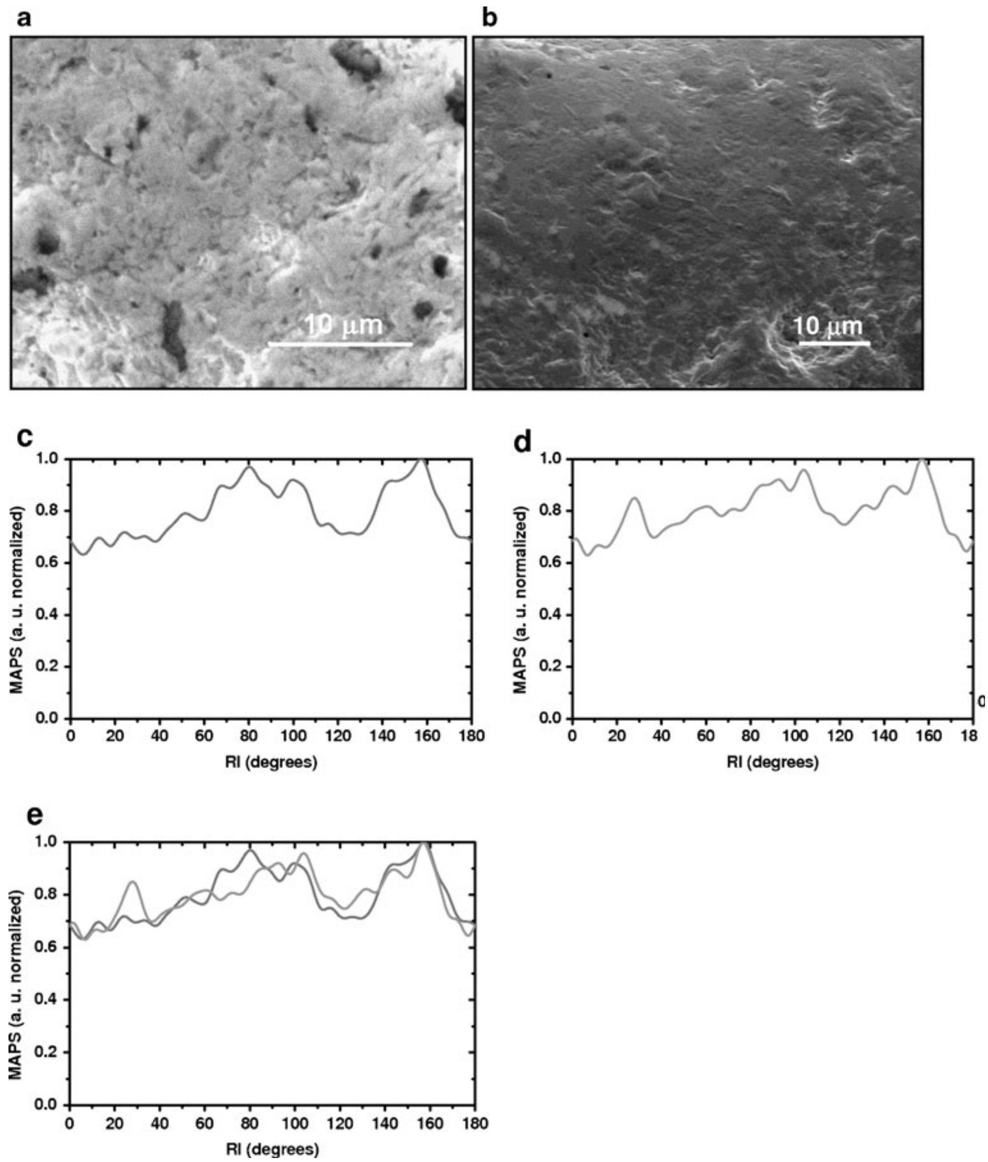

Fig. 5 Results of RIMAPS analysis of wood worked with rhyolite tool. **a** and **b** are SEM micrographs of two different surfaces of stone tools with wood wear traces. **c** RIMAPS spectrum of first image. **d** RIMAPS spectrum of second image. **e** Comparison of spectra **c** and **d** presenting the same general saw-tooth form. RIMAPS shows a remarkable coincidence between both worked tools

RIMAPS and Variogram to characterize the typical surface patterns and quantify the resulting topography after different wear processes on lithic artifacts.

Materials and procedures

In order to build up an analytical framework for the evaluation of the reliability and applicability of RIMAPS and Variograms to the study of lithic artifacts, we carried out an experimental program using non-retouched flakes of metamorphosed rhyolites obtained by direct percussion. These rocks were exploited by hunter–gatherer–fisher societies who lived on the Magellan–Fuegian archipelago (Southern South America) since the seventh millennium before present up to the beginning of the twentieth century (Álvarez 2003; Orquera and Piana 1999).

The rhyolites are dominantly composed of a cryptocrystalline groundmass of quartz and plagioclase in which quartz crystals are embedded (Terradas 1996). The process of use-wear development on these metamorphic rocks is relatively slow compared with the silex. Nevertheless, after 30 min of use, most of the experimental tools exhibit a quite diagnostic pattern of use-wear traces, even though they display different degrees of development according to the worked material (Mansur 1999).

For the purpose of this study and with the aim to reducing the number of variables, the experimental stone tools were used to scrape fresh bone, fresh wood, and fresh hide. The raw material remained constant and each instrument was held at 45° angle to the working surface. Before the observation the stone tools were handwashed with water and mild detergent and then they were cleaned with ethyl alcohol in an ultrasonic tank. These cleaning procedures have shown to be effective in the case of these rhyolites; therefore, more aggressive methods were avoided. The pieces were initially examined under an incident light microscope, at a range of ×50–×500, with the aim of recording the extent and the distribution of the use-wear traces as well as their degree of development. This procedure allowed us to select 15 artifacts (5 for each worked material) that were used for 30 min and exhibited a well-developed micropolish area.

Even though light microscopy (LM) is the first and accessible microscopic tool for artifact inspection, the impossibility of obtaining images completely in focus and without depth of field problems, restricts its application to qualitative characterization. Hence, the use of environmental scanning electron microscope is fostered to obtain quantitative results. Figure 2 illustrates the characteristics of LM images showing two different images of lithic tools.

Afterwards, the selected sample was observed by a scanning electron microscope (SEM) and 150 digitized micrographs were taken from different areas of each tool that included polished and unpolished surfaces at different magnifications ranging from ×100 to ×4,000. It is important to note here that the analysis of the unused parts of the experimental artifacts are considered reference patterns in order to elucidate which length scales emerge or disappear as a consequence of tool use as well as to compare the peak intensities and their angular positions obtained by RIMAPS analyses.

Results

Following the aforementioned procedures, RIMAPS was performed on SEM images of used and unused lithic

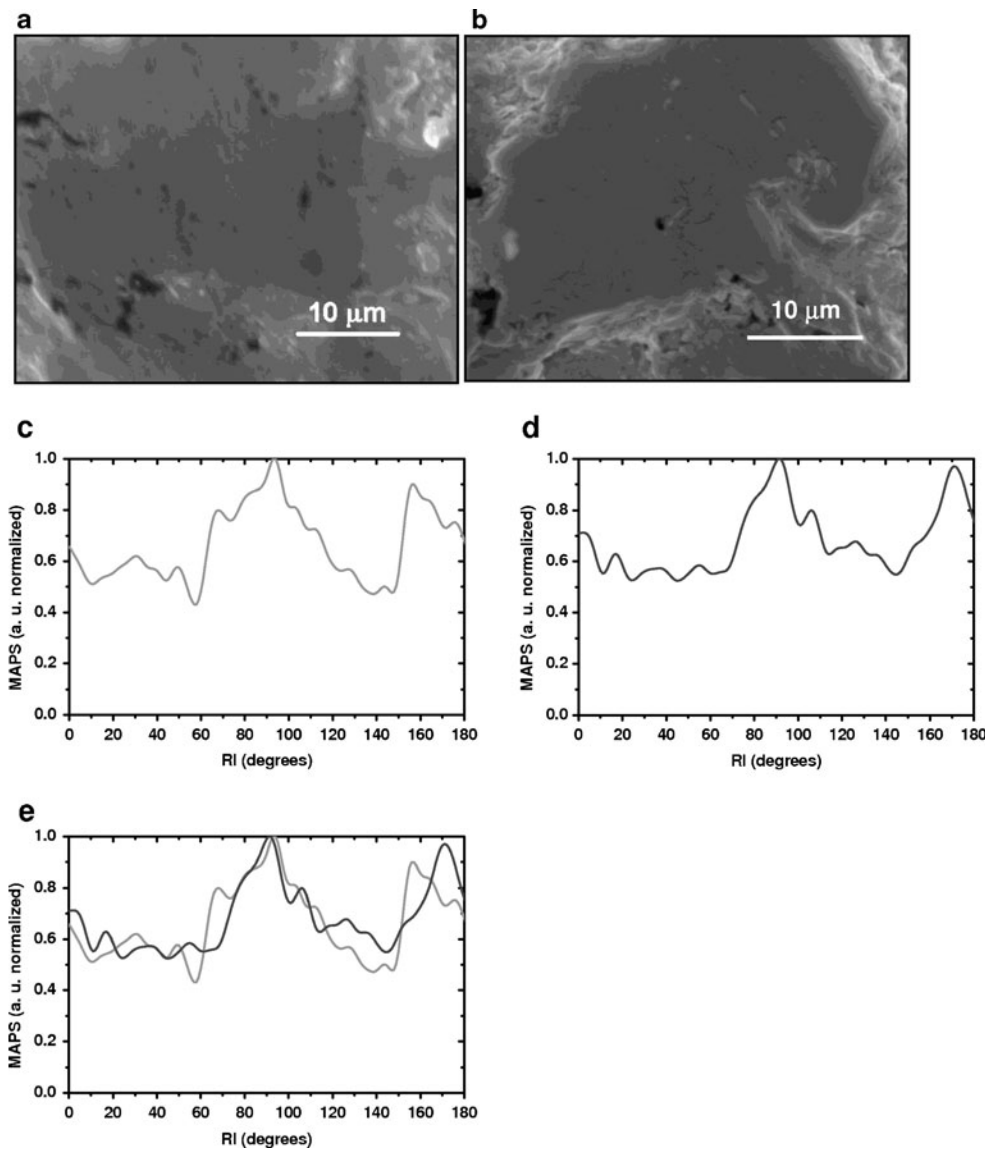

Fig. 6 RIMAPS analysis of rhyolite tools used on bone: **a** and **b** SEM micrographs of two different surfaces of tools with bone wear traces; **c** RIMAPS spectrum of first image; **d** RIMAPS spectrum of second image; **e** Comparison of spectra; **c** and **d** showing the same general form of two triangular blocks of peaks. Coincidence between both general shapes can be well detected using RIMAPS

surfaces (Figs. 3–6). In all cases, digitized images of rhyolite flakes used to scrape different materials such as hide, bone, and wood were rotated 180°. Results shed light the fact that the surface pattern corresponding to an unused artifact is always modified, and new distinctive, characteristic patterns appear representing the particular task performed with the lithic tool. The comparison between the RIMAPS spectra of the different surfaces after working on hide, wood, and bone, and an unworked area of the same lithic tool are shown in Fig. 7.

Hide-working has two peaks close to 30° and 160° that are present in unused surfaces (Figs. 4 and 7a). The new pattern has also a baseline $y_0 \geq 0.6$, given by all the minimum values, and tends to form four wide peaks of nearly the same intensity. Although both RIMAPS spectra displayed in Fig. 4 (c and d) show subtle differences (the "c" spectra has four well-defined peaks while "d" spectra exhibits a smoother shape), coincidences can be seen between the first two minimum values, (that bound the first two blocks) and the maximum values of the third and fourth blocks of the "c" spectra in relation to the peaks of the "d" spectra.

When rhyolite tools are used on wood (Figs. 5 and 7b), the prevailing peak is located at 160° and the intensity of the peak around 30° is diminished. Now, the pattern reduced mainly to two peaks of higher intensity and superimposed on a triangular saw-tooth general shape of the spectrum, with a base line $y_0 = 0.6$.

In the case of bone-working, the baseline is lower with a value of $y_0 \leq 0.5$; the pattern has only two wide peaks with similar intensity at 90° and in 155° (Figs. 6 and 7c).

If comparison is made with the RIMAPS results obtained analyzing an unused area of the same lithic tool (Fig. 7), it can be observed that in all spectra corresponding to the cases of used surfaces, the peaks associated with the pre-existing topography of the rock are always present. The use of lithic tools on different materials causes the variation in the intensity of the peaks characterizing the topographic pattern of unworked rock. There exist two peaks located around 30° and 160° having the higher intensity among the peaks corresponding to the unused surface of lithic tool. These peaks delimit the angular region of 130° wide of the tool edge. In this region, the different processes of hide, wood, and bone-working, introduce modifications to the spectrum shape and produce the appearance of new peaks corresponding to the nature of worked material.

The traces produced by each working process introduce new peaks in the edge region, while the abrasive nature of the worked surface modifies the natural roughness of the stone, as in the case of bone (Figs. 6 and 7c) where the peaks around 30° and 160° diminish their intensity as a direct consequence of the polishing effect. From the previous results, it can be said that all the variations in shape and intensity of peaks allowed discovering different patterns related to the working motion of the tool as well as from micropolish formation. As the pattern produced on any surface is strongly dependent on the motion follow by the tool, and in order to compare the results emphasizing the different nature of worked materials, the lithic tool was always used following linear movements. RIMAPS detects the different characteristics of the microwear traces

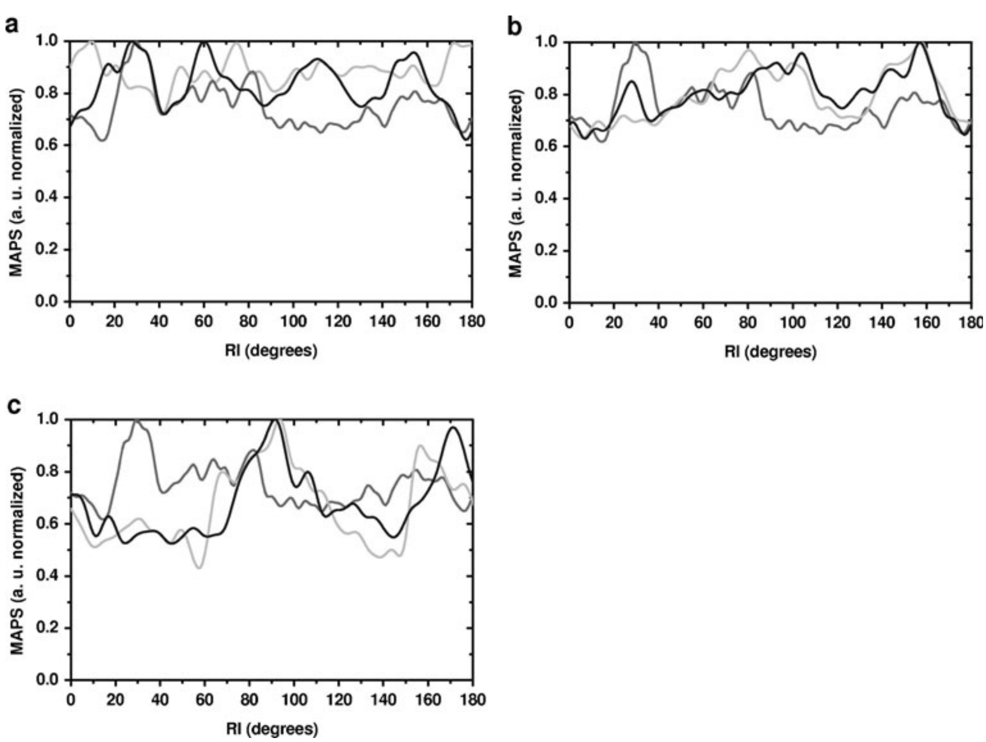

Fig. 7 Comparison between the RIMAPS spectra of the different surfaces after working on **a** hide, **b** wood, and **c** bone, and a non-worked area of the same lithic tool. *Black and gray light lines* correspond to worked surfaces; *gray lines* correspond to unworked surfaces

produced on the surface of the experimental tool after scraping it on hide, wood, or bone that are graphically expressed by the position of the baselines as well as the general shape of the peaks. In all cases, RIMAPS gives the typical working pattern that modifies the pre-existing natural topography of the stone, representing a true "fingerprint" of each process.

The RIMAPS study is complemented using Variogram analysis (Tables 1, 2, and 3). This method gives the scale lengths that characterize the topographic patterns on the surfaces under study. It can be derived from Table 1 that some values obtained from an unused surface appear also in the micropolished region (for all worked materials), which means that some natural lengths of the stone remain unchanged for wood, bone, or hide materials. But at the same time, in all the lithic artifacts new lengths appear representing the distinctive characteristic of the material that was worked.

The pattern on an unworked stone has lengths ranging from 1.17±0.18 to 32.89±4.00 μm. In the case of wood-working, the shortest lengths appearing on the unworked tool are present, and three new lengths characterize the polishing pattern that arises on the stone: 3.21±0.20, 5.01±0.31, and 8.73±0.54 μm. In the bone-working case, the shortest length is not present and this process also introduces three new lengths different from the unworked surface and similar to the wood-working case: 3.00±0.22, 4.77±0.35, and 8.94±0.66 μm. Results obtained when hide has been worked show that only three scale lengths corresponding to the rhyolite stone are present and two new lengths appear: one that is common to the cases of wood and bone (4.90±0.76 μm) and the other distinctive of this process of working on hide (20.47±2.49 μm).

Discussion

The combined information obtained from RIMAPS and Variograms provides reliable data in order to detect differences between micropolish topography in relation to the worked material. These results are remarkably consistent with the mechanisms of polish formation as well as texture and microtopographic characteristics of use-wear traces.

It must always be taken into account that RIMAPS gives the main angular directions of the microtopography and the Variograms the length scales of the microtopography. One of the most outstanding results given by RIMAPS spectra is the coincidence of peak distribution with the visual appearance of micropolish surfaces left by different worked materials.

As it has long been established by many researchers who dealt with use-wear analysis, bone polish appears bright in sharp contrast to the unaltered surface of the rock and it spreads only on the high points of the microtopography of the edge. The RIMAPS spectra show precisely well-defined and separate peaks reflecting that distributional and topographical pattern. On the contrary, wood-working polish is commonly gently domed, very smooth in texture, and covers the elevations as well as the depression of the surface; the triangular saw-tooth general shape of the RIMAPS

Table 1 Scale lengths obtained from Variogram analyses for wood-working

Unworked (μm)	Wood (μm)
1.17±0.18	1.10±0.07
2.26±0.36	2.34±0.14
–	3.21±0.20
4.02±0.63	3.57±0.22
–	5.01±0.31
6.36±1.00	–
–	8.73±0.54
9.42±1.49	10.06±1.22
12.92±2.04	–
14.71±2.32	–
–	–
26.82±3.26	24.04±2.92
32.89±4.00	–

Table 2 Scale lengths obtained from Variogram analyses for bone-working

Unworked (μm)	Bone (μm)
1.17±0.18	–
2.26±0.36	2.50±0.19
–	3.00±0.22
4.02±0.63	–
–	4.77±0.35
6.36±1.00	5.31±0.39
–	8.94±0.66
9.42±1.49	–
12.92±2.04	–
14.71±2.32	14.54±1.08
26.82±3.26	24.45±1.82
32.89±4.00	29.70±2.21

Table 3 Scale lengths obtained from Variogram analyses for hide-working

Unworked (μm)	Hide (μm)
1.17±0.18	–
2.26±0.36	2.29±0.36
4.02±0.63	–
–	4.90±0.76
6.36±1.00	–
9.42±1.49	–
12.92±2.04	11.84±1.84
14.71±2.32	–
–	20.47±2.49
26.82±3.26	23.50±3.66
32.89±4.00	–

spectrum reveals this appearance and fits the model of micropolish formation process.

Finally, the spectra obtained from the tools that were employed to scrape hide are also consistent with the traces observed in the process of working this kind of material. The microtopographic characteristics of hide polish—a polish which generally extends along the edge and that tends to cover the entire bevel homogeneously—are highlighted by RIMAPS analysis; the spectrum exhibits regular peaks that reproduce the appearance of this polish.

Quantitative results, given by Variogram analyses, shed light on the differences in the hardness of the materials that have been worked with the lithic tools. As hide is the softest and most abrasive material used, the traces on the stone due to the scraping process masks many of the length scales observed on an unworked rhyolite surface, which is not the case when wood and bone are used. Even though differences between the different worked materials are detected, the increasing of the working time will certainly introduce more remarkable and distinctive differences.

Conclusions

The general aim of this research was to introduce two new imaging methods RIMAPS and Variograms to mathematically characterize distinct patterns of worked materials on used edges of lithic artifacts. These preliminary results show the robustness and the potential of both analytical procedures to measure and characterize a lithic surface.

The ongoing research presented here, in first instance, give support to the models of polish formation as well as the visual appearance of the traces. This study reveals, in quantitatively terms, the topographic transformation produced on a lithic surface as a consequence of its usage. Moreover, it strengthens the view that different patterns are related to the worked material, as Semenov and Keeley had pointed out in their pioneering works. These patterns can be detected and measured by providing the alignment of each side of the typical geometrical shape and its orientation on the surface, in the case of RIMAPS technique or the common scale length applying the Variograms method.

On the other hand, this research unveils that variables and criteria often employed by use-wear analysts in order to identify the activities performed by a stone tool, such as brightness, smoothness, distribution, and microtopographic characteristics, have quantitative correlates. Therefore, despite of the critiques related to the inherent subjectivity of observer regarding the identification of use-wear traces, this study highlights the operative and analytical significance of the qualitative criteria in order to yield reliable interpretations of use-wear evidence and the context of use of lithic tools. Consequently, RIMAPS and Variograms could become powerful and supportive tools that can be successfully applied in use-wear research.

In this sense, we expect in the future to extend this new line of research to images obtained through an optical microscope, making it easier to use RIMAPS and Variogram for wear trace characterization without the aid of scanning electron microscopy. Furthermore, it will be necessary to obtain larger experimental and archaeological lithic samples from different raw materials used to work several resources in order to adjust and improve these analytical procedures and to achieve reliable interpretations of past technologies.

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