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Cleaning your tools doesn’t mean that the tools are clean. A qualitative and quantitative perspective using confocal microscopy[☆]

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ABSTRACT

Use-wear analysis has traditionally been criticised for relying heavily on subjective interpretation of the marks present on artefact surfaces. In recent years, confocal technology has started to make it possible to quantify and partially resolve this subjectivity. However, certain methodological aspects of great relevance for the analysis, such as the cleanliness of the pieces, have been significantly underestimated. This work aims to quantitatively verify whether qualitatively reliable – although not perfect- cleaning processes can modify the roughness readings of the surface of the tools. For this, 3D ISO 25178 parameters were analysed on an experimental rock crystal sample obtained with a confocal optical LED profilometer. The differences that we have found indicate the need not only to wash the samples, but also to check the degree of cleanliness of the materials once they are washed, which leads to the qualitative and especially quantitative importance of an adequate cleaning procedure before analysing the materials.

1. Introduction

Use-wear studies aim to investigate the deformation of archaeological objects resulting from their use, with the primary objective of determining whether an object has been used (among others: Semenov, 1964; Keeley, 1980). If this information is positive, and it can be confirmed that the piece was used, an attempt will be made to determine on what material, and the activity it was used for. However, the microscopic examination of use-wear traces presents a challenge due to the presence of equifinality, where similar traces can be produced by different processes (e.g.: Keeley and Newcomer, 1977; Newcomer et al., 1986; Shea, 1988). These types of processes may include the technological process of knapping and retouching of the artefacts (Ibáñez Estévez et al., 1987; Byrne et al; 2006; Rots, 2010; Morales and Vergès, 2014; Akoshima and Kanomata, 2015) and some post-depositional processes or activities that are not strictly functional, such as transport (Mazzucco and Clemente-Conte, 2013; Pyzewicz and Grużdź, 2014). Consequently, in recent decades, the field has seen a significant new shift – initially originated in the decade of the 80′s – toward surface metrology, influenced by the latest advances in 3D microscopy and imaging technologies (among others: Cowley and Opitz, 2013; Evans et al., 2013; Goodall et al., 2015; Galland et al., 2019; Macdonald et al., 2019; Itamiya et al., 2022; Calandra, 2022; Bustos-Pérez and Ollé, 2024). This is because surface metrology provides quantitative, high-resolution data for detailed and objective analysis of surface features, helping to differentiate traces from similar materials, such as for example bone and antler, that can be difficult to identify (Vaughan, 1981, 1985). A key part of this change has been the introduction of confocal microscopy, a non-contact surface imaging technique that captures precise three-dimensional surface topography.

However, this transition has introduced new challenges. While human observers could be able, with exhaustive training, to filter out noise caused by surface contamination, metrological instruments cannot. Dirt and residue on a surface can introduce significant noise into measurement data, potentially leading to misclassification of wear types or erroneous conclusions about tool use. Thus, the importance of meticulous surface cleaning has increased alongside the rise of metrological techniques. Ensuring that surfaces are free from contaminants is now a prerequisite for obtaining reliable and meaningful data, particularly when using confocal microscopy. Moreover, it is relevant to mention that this issue and its importance were discussed in depth during the first years of the development of traceology (Keeley, 1980; Anderson-Gerfaud, 1981; Plisson, 1983, 1986; Plisson and Mauger, 1988; Levi-Sala, 1986, 1996; van Gijn, 1986, 2014), especially with regard to the possibility that dirt could obscure functional evidence.

This work focuses on investigating the effects of different cleaning

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stages on the 3D ISO 25178 parameters (ISO 25178. , 2021) using multiple points across three distinct rock crystal flakes. The aim is to investigate whether the cleaning procedures have a significant effect on the surface parameters, highlighting the importance of proper cleaning, even of the manipulation dirt, before the subsequent analysis of materials. In addition, the study seeks to explore the existence of an underlying classification scheme that takes into account the robustness of parameter values in the presence of dirt-induced noise.

We show how dirt, both due to lack of cleaning and unsatisfactory cleaning, can not only hide functional evidence (Pedergnana et al., 2016; Mateo-Lomba et al., 2022), but also generate layers that are visually identical to the traces themselves (Fig. 1). These, as elements adhering to the surface of the pieces, can ~~also~~ generate microtopographic changes, which will consequently alter the results obtained in

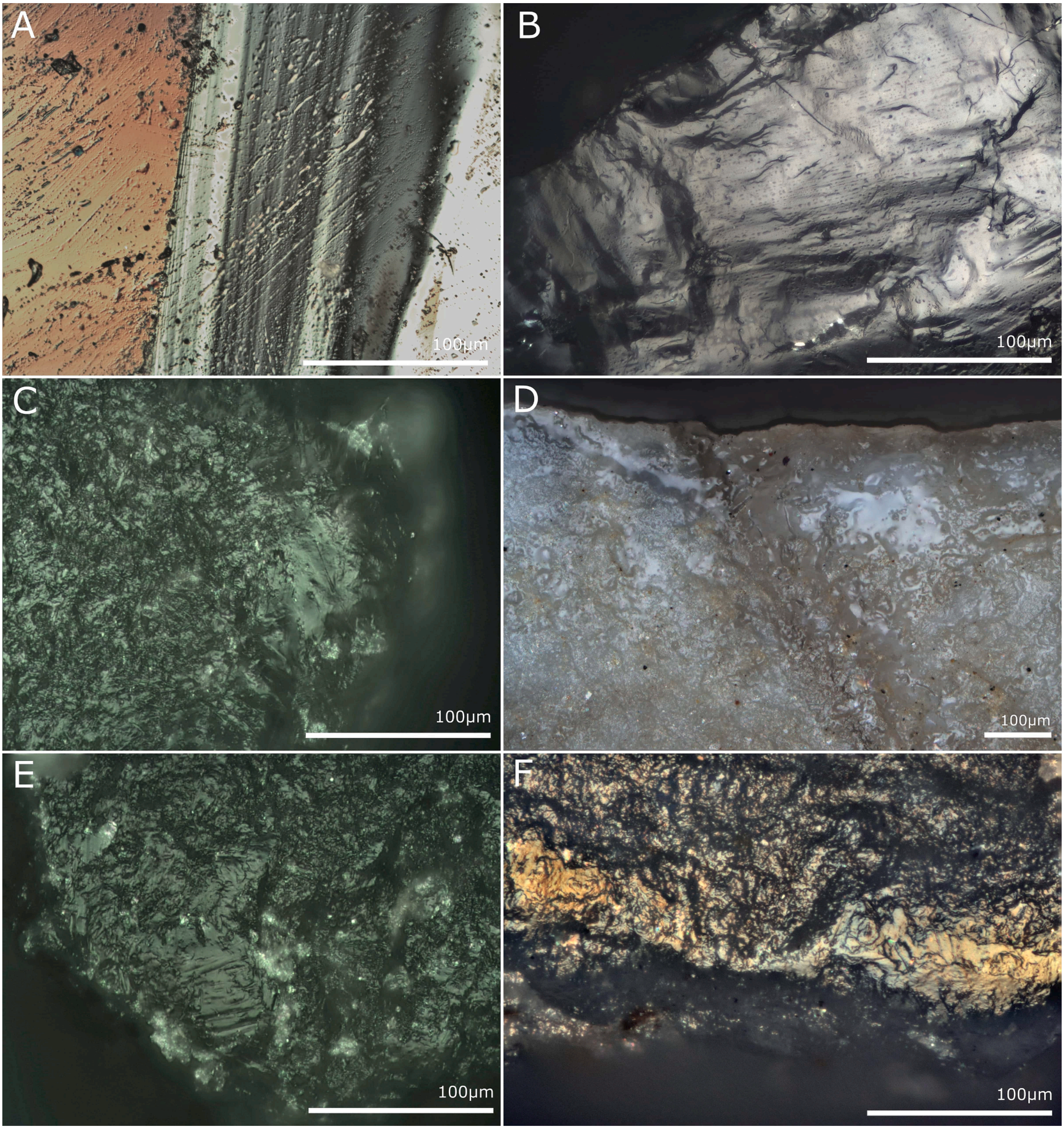

Fig. 1. Examples of images taken with the optical microscope of clean parts that, due to a poor washing process or accidental contact with the equipment used for cleaning, still show dirt. A and B: Greasy lines that mimic striations on rock crystal (A) and milky quartz (B). C, E and F: Slightly flattened and banded dirt remnants imitating polishing and polishing with striations very similar to those reported in some publications. D: Nail polish to mark the tool repositioned on the cutting edge despite having been cleaned with a solvent (acetone). For the OM images we used a Zeiss Axioscope A.1, Z-axe motorised; micrographs were taken with LD Epiplan lenses HD DIC, 20x/0.4 (D) and 50x/0.5 (A, B, C, E and F).

both traditional and quantitative traceology work. It is therefore crucial to minimise the impact of extraneous information, such as dirt, which can potentially lead to erroneous interpretations and false results.

Cleaning products and protocols frequently used in the IPHES traceology group included different variants depending on the sample to be analysed (e.g. Ollé and Vergès, 2008; 2014; Tumung et al., 2015; Ollé et al, 2016; Fernández-Marchena and Ollé, 2016; Fernández-Marchena, 2021, Pedergnana and Ollé, 2017; Mateo-Lomba et al., 2022). Here we used a protocol specifically designed for this experiment, consisting of washing with 130- vol hydrogen peroxide and acetone which, like the neutral soap in other cases, is always used in individual zip-lock bags inside an ultrasonic tank. We also introduced the use of the cotton swabs in stage 2, which we would never use to clean the edges of the archaeological or other experimental pieces.

1.1. *Quantitative measurements and ISO standards on areal surface texture*

Surface analysis plays a critical role in various scientific and industrial applications, providing valuable insights into the characteristics and quality of materials. In particular, the evaluation of surface parameters based on international standards, such as the ISO 25178 parameters, has become a widely accepted method for quantifying surface properties (ISO 25178. , 2021). Therefore, it appears to be an interesting quantitative approach in the study of use-wear in archaeological material since it has traditionally been accused of relying heavily on subjective interpretation.

Quantitative measurements started with Gustav Schmaltz's light-section microscope and profilometer (Schmaltz, 1936), which made possible detailed surface profile measurements. This instrument, developed in collaboration with Carl Zeiss, produces a light sheet using a slit. The reflected light has the shape of the profile of the surface and can be recorded by a camera. In this way, geometries can be measured and defects in such objects can be detected (Borlinghaus, 2021). By the mid-20th century profilometers started using electronics to process surface roughness data and, despite its limitations, the center-line average roughness parameter (*Ra*) became a widely accepted parameter thanks to its simplicity (Blunt, 2003).

In the 1960 s and 1970 s, digital computing revolutionized surface characterization and researchers developed multiple parameters to describe surface features. However, this led to over 100 poorly defined parameters showing the need for global standards to improve communication and use (Whitehouse, 1981; Blunt, 2003).

The transition to 3D surface characterization began in the 1980 s, with pioneers like Dr. Thomas and Dr. Stout creating early systems. However, major stylus instrument manufacturers initially resisted, considering 3D analysis as impractical until the 1990′s, when commercial systems were introduced by companies like Rank Taylor Hobson and Somicronic, integrating visualization techniques and functional parameters (Stout et al., 1993; Blunt, 2003; Borlinghaus, 2021). Since then, numerous manufacturers have entered the market in all the fields of instrumentation (among others: Sensofar, Olympus, Leica).

The European Community supported BCR research contract in 1990 established the foundation for standardizing 3D surface parameters, resulting in the "Birmingham 14″ parameters (Stout et al., 1993; Blunt, 2003; Thomas, 2008; Leach et al., 2015). These parameters described amplitude, spatial, and hybrid properties of surfaces and influenced the new ISO standards.

ISO (the International Organization for Standardization) is an international federation responsible for developing International Standards for various domains, including technology, scientific testing processes, working conditions, and societal issues. The ISO 25178 standard, titled "Geometric Product Specifications (GPS) – Surface texture: areal" (ISO 25178, 2021), represents a collection of international standards addressing the analysis of 3D areal surface texture and the corresponding applied descriptive parameters.

1.2. *Confocal microscopy and surface texture*

Surface topography refers to the overall structural characteristics of a surface treated as a continuous range of spatial wavelengths. More precisely, a surface comprises a primary shape or form, accompanied by varying levels of texture elements named waviness and roughness. Roughness primarily refers to fine-scale surface texture features (short-wavelength), while waviness pertains to undulations or larger-scale deviations (longer-wavelength).

The selection of relevant spatial wavelengths for measurement and control depends on the specific application, as different surface contributions may be of varying importance (Wolf, 2020; Pagani et al., 2017; Leach, 2013; Mainsah et al., 2001). However, there is no fixed universal numerical value below which we consider texture to be roughness and above which we call it waviness. It depends on the object whose surface we are studying, and the results depend critically on the choice of filter parameters set by the researcher. That's why comparing new results with published studies can provide valuable guidance on which values and parameters to use, supporting further comparability of the data (e.g. Stevens et al., 2010; Pedergnana et al., 2020b; Ibáñez and Mazzucco, 2021).

Moreover, the surface topography characterisation involves the use of specialised equipment to calculate all the numerous parameters. Traditional stylus instruments or profilometers can only measure surface height along a line in two dimensions. In contrast, optical profilers have the capability to measure in three dimensions, capturing data over an entire area (Blateyron and Caulcutt, 2006).

While profile measurements can be useful in showing changes in some processes, a more comprehensive understanding of surface functionality can be gained by analysing the areal surface topography. For example, a discrete pit observed in a profile may actually be a valley when examined in the context of an areal surface map. The functional implications of such features may be more significant than initially perceived. Additionally, areal measurements provide more statistical significance compared to equivalent profile measurements due to the larger number of data points and their closer representation of the actual surface (Leach, 2013).

1.3. *Filter application*

A filter is a tool used to exclude wavelengths above or below a certain frequency. Filtering is a process required for several purposes in the surface texture analysis, but the main reason for using a filter is to separate long-scale from short-scale components (separate waviness from roughness) and calculate parameters according to the specification (Blateyron, 2013; 2014). For areal surface parameters, wavelengths are usually analysed between an upper and lower nesting index (the cut-off for 2D) after using a S-filter, which attenuates component scales that are shorter than the nesting index, and a L-filter, which attenuates the longer ones. The nesting index or cut-off value must be chosen wisely in order to separate two wavelength populations and not cut right in the middle of one of the populations. In other words, if the workpiece contains roughness and waviness, the spectrum will show one population of wavelengths for the roughness and another one for the waviness. The correct value should be specified so that it separates the two populations without distorting them.

In addition to S-L filters, an area measurement requires the use of an F operator. When the form is just a line segment or a plane, this operation is called levelling. When the form is non-planar, it is called form removal (*SensoView 2.1: Form removal*). Specifications of surface texture are made on a flat surface, regardless of the original geometrical form before carrying out the metrological analysis. This operation consists in modelling the shape and associating it with to the cloud of measured points in order to subtract the form.

2. Materials & methods

A total of 30 sequential analysis were carried out randomly choosing 30 points from 3 different experimental rock crystal flakes (approximately 10 points per piece) free of use-wear. The same point was scanned using a Confocal Sneox 090 LED optical profilometer at 100X (0.8NA; 4.5 mm WD; 4000 *μm* Max. range) in four different stages: without cleaning the manipulation dirt out of the piece (stage 0), with the piece cleaned first with H_2O_2 (130 vols.) and then with acetone – both in the ultrasonic tank with individual zip bags – (stage 1) followed by an additional cleaning with acetone applied with a soft hyssop (stage 2). The stage 3 corresponds to replicated measurements of stage 2 in order to control potential noise introduced by the microscope (Figs. 2-4; SI:Figs. S1–S6). Overall, a total of 120 acquisitions were made, including the 4 different stages (stage 0–3) for each of the 30 experimental points (30 sequences).

The surface parameters (Table 1) were computed from a selected surface representing 130 x 130 μ*m* for all points (ISO 25178, 2021). The mean of the parameters was calculated for three consecutive acquisitions for the same point in order to reduce the Non-Measured Points (NMP). All measurements were > 99 % so they were used without applying any restoring algorithm. Sensitivity was set at level 3 with a resolution of 5Mp in order to avoid spikes that would cause measurement outliers. To relocate all points in each sequential analysis, we employed a three-dimensional printed gear stage (supp) in conjunction with a paste mold created from the artifact's negative using Provil novo Putty regular set (Kulzer GmbH, Hanau, Germany). The mold is secured within a plastic box that is placed on top, supported by a wooden frame attached to the surface of the platform (Fig. 5; SI: Figs. 7-9).

This approach not only ensured the part was positioned in its original orientation but also maintained consistent inclination angles for the tool in each sequence (Francès-Abellán and Lozano, 2024). When necessary, the samples were repositioned to maintain consistent orientation across low to high magnifications (5X, 10X, 20X, and 100X).

To achieve uniform orientation of the samples, microscopic images were captured using all objectives of the microscope, considering various reference points (such as edges, undulations, and fissures). This method ensured that the surface photographed at each objective magnification aligned precisely with the images obtained in the previous sequences.

When the acquired surface reached enough quality, an F operator was applied to remove the form. The S and L (Gaussian) filters were then applied to remove short and long wavelengths respectively. The nesting index of the S-filter was set as 0.25 μm and the nesting index of the L-filter was set as 8 μm (Fig. 6).

2.1. Statistics

All analyses were conducted using both IBM® SPSS® Statistics v. 22.0 (IBM) and PAST 4.0.3. The significance level was set to 0.05.

A Shapiro-Wilk test indicated that most of the parameters (92.59 %; 25 of 27 parameters) were non-normally distributed, from what the standard F-test is inappropriate (Keselman et al., 1998; Keselman, 1998; Wilcox and Keselman, 2003). Consequently, Friedman test – a non-parametric alternative to repeated-measures ANOVA – was applied (Hays, 1988; May et al., 1990; Friedman, 1937). To know precisely which groups differ from each other Wilcoxon pair-wise test with Bonferroni correction was used.

3. Results

Significant differences were observed among the cleaning stages for all parameters except *Std* (Fig. 7) and *Sku* (Friedman test: $\chi2$; $p > 0.05$. Table 2).

Specifically, these statistical differences appear when comparing the initial, uncleaned stage (0) with stages with at least one cleaning procedure (1–3) for (see Table 1 for definitions) *Sa, Smean, Ssk, Sal, Str, Sdq, Sdr, Sratio, Vmc, Vmp, Smr2, Vvc, Vv, Smc* (Fig. 8)*, Sk, Smr, Svk, Vvv* and *Smr1* (Wilcoxon test: W; $p < 0.05$. S.I. Table 1).

Additionally, significant differences were also observed for the parameters *Sp, Sz* (Fig. 9)*, Sv* and *Spk* between the first stage (1) and both the second stage (2) and the third stage (3) (Wilcoxon test: W; $p < 0.05$. S.I. Table 1) besides (0) with (1–3). No significant differences have been shown between the second (2) and the third stage (3) in any case (S.I. Table 1). These results led to the classification of the parameters according to their sensitivity to dirt (Table 3). Group 1 corresponding to the dirt-sensitive parameters; Group 2 to the extreme dirt-sensitive parameters, and Group 3 to the non-dirt-sensitive parameters.

In exceptional cases (*Sq, Sxp*), statistical differences were observed between the first stage (1) and only one of the replicates (2,3). This discrepancy can be attributed to the significance level, where in one replication (e.g. 2) the p-value may slightly exceed 0.05, while in the other replication (e.g. 3), it falls just below 0.05. In such instances, we believe that these parameters should be included in the second group.

4. Discussion

The results of this study show that cleaning procedures have a

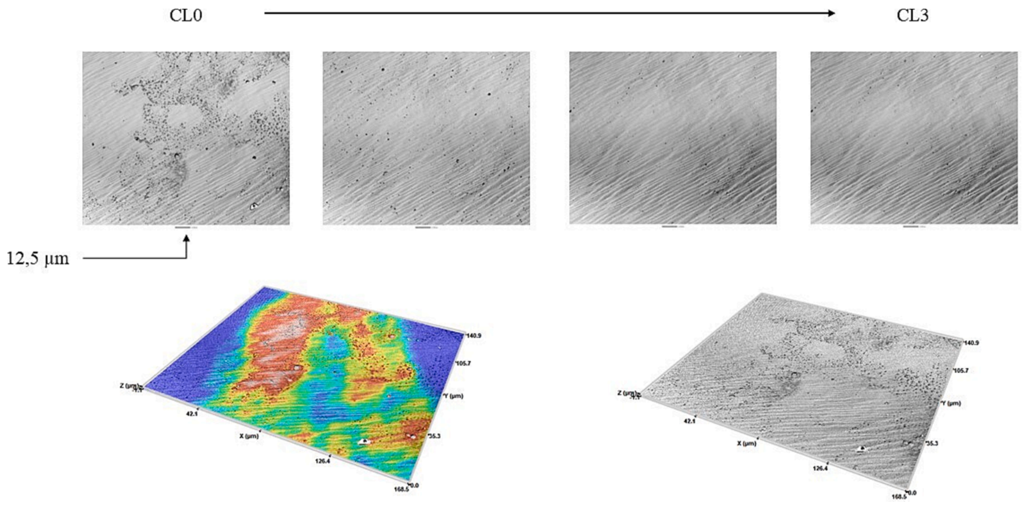

Fig. 2. TOP: 168,5 x 140,9 μm square sample (for illustrative purposes) of the second quartz piece (Q2) Point 4 in all four cleaning stages (0–3) 2D. BOTTOM: 168,5 x 140,9 μm square sample of the second quartz piece (Q2) Point 4 in stage 0 colour topography 3D and black-white 3D. All images acquired using Sneox 090 100X.

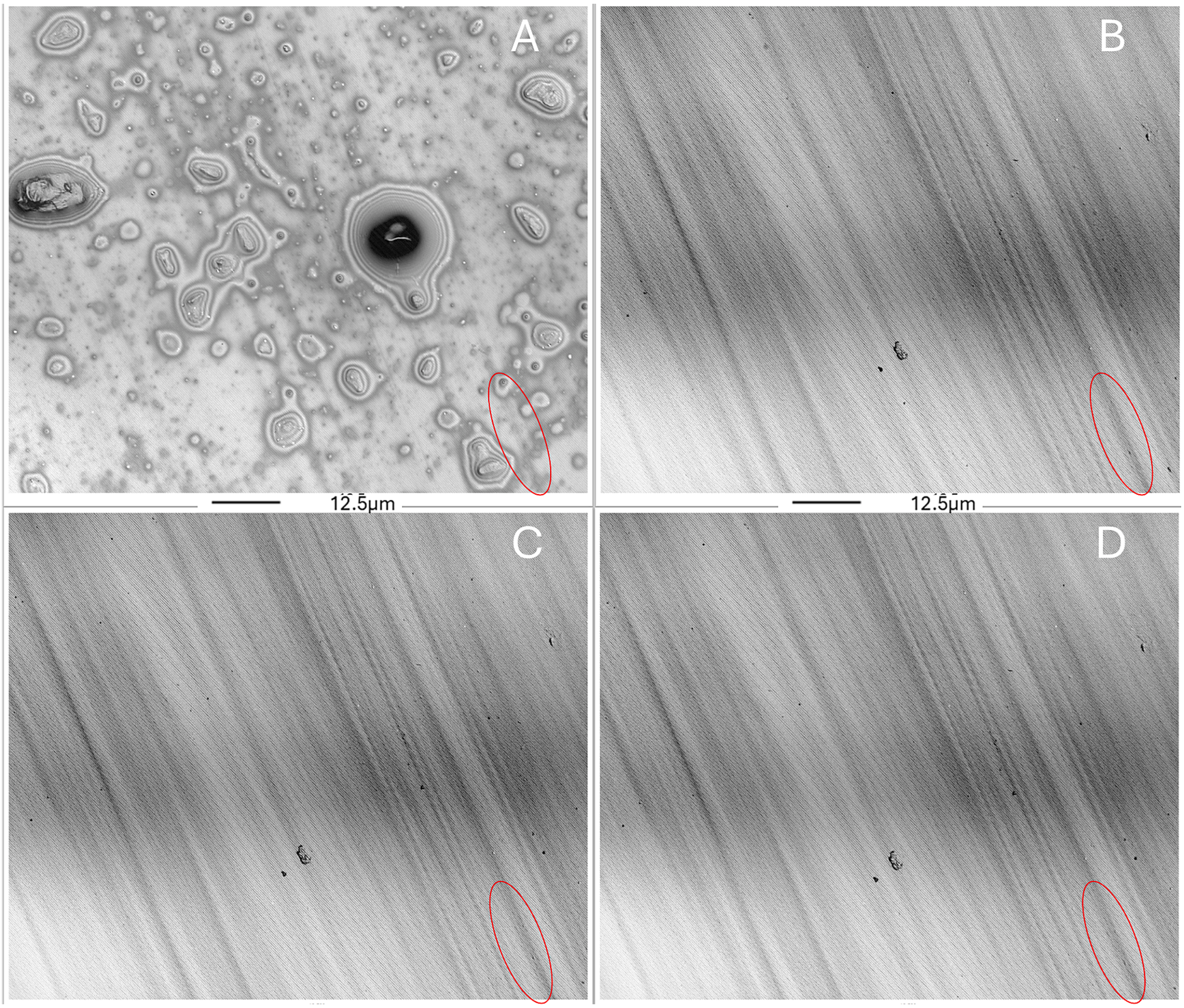

Fig. 3. TOP: 168,5 x 140,9 µm square sample of the first quartz piece (Q1) Point 2 in all four cleaning stages (0–3) in black-white. A: stage 0; B: stage 1; C: stage 2; D: stage 3. In red there are some examples of matching features. All images acquired using Sneox 090 100X.

significant effect on various surface roughness parameters, enriching our understanding of the right technical specifications to be used. This is particularly relevant as the methodology for quantitative studies is still being developed and there is still no clear consensus among experts. These results complement other crucial variables to be considered, including factors such as the extraction area and magnification levels (Borel et al., 2021).

This work stems from an issue detected in our own laboratory analyses, where through trial and error, we have found that the lack of cleanliness or improper cleaning of samples is not only due to failure to follow protocols but also because perfect cleanliness does not exist. There are many uncontrollable variables such as particle dispersion, the quality of laboratory products, improper drying of samples, or handling of specimens that can cause contamination even on freshly cleaned pieces. It is therefore important for the analyst not only to know how to use microscopes correctly and identify deformations in the materials to be analysed, but also to be able to identify possible contaminants and dirt residues present in the materials.

It is noteworthy that the majority of the surface roughness parameters fell into Group 1, which comprises parameters considered to be dirt-sensitive. The dominance of these parameters (Group 1) highlights a critical aspect of use-wear analysis that may have been underappreciated until now. It emphasises that many of the metrics traditionally used in quantitative surface analysis are susceptible to dirt, including manipulation dirt. When analysing artefacts with these parameters, a correct and effective cleaning procedure is mandatory. Furthermore, when analysing with Group 2 parameters the meticulousness of the cleaning procedures becomes paramount. In these cases, even small residues or contaminants can lead to substantial biases in the interpretation. This demonstrates the importance not only of cleaning artefacts, but also of assessing the degree of cleanliness prior to analysis. Failure to do so can lead to erroneous interpretations of surface wear and use activities. Researchers and analysts should be particularly cautious when dealing with dirt-sensitive parameters, but even more so with the extremely dirt-sensitive parameters, as even slight contamination can skew results and one protocolary cleaning procedure may not be enough.

This work also highlights how the quality of the quantitative results is also subject to cleanliness. The mimicry of dirt with traces or even various minerals can lead to misinterpretations not only under the optical microscope. The confusion of these elements with use-wear traces cannot be solved by simply changing the optical microscope for a confocal or digital microscope and vice versa. Without thorough training in use-wear recognition and residue mimicking traces, this problem can only be solved by resorting to the scanning electron microscope and its backscatter detector or EDX microanalyses (Borel et al., 2014;

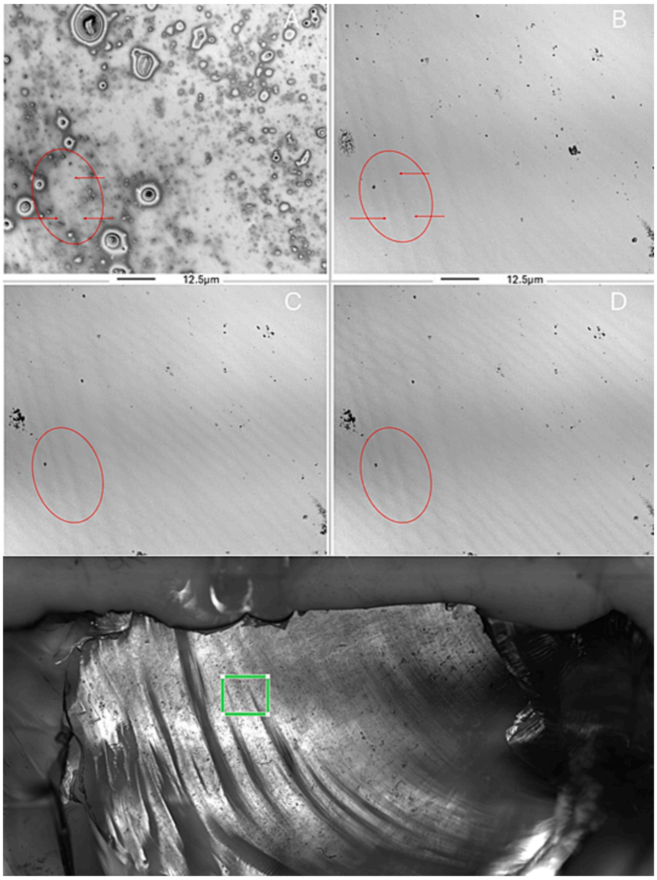

Fig. 4. TOP: 168,5 x 140,9 μm square sample of the first quartz piece (Q1) Point 2 in all four cleaning stages (0–3) in black-white. A: stage 0; B: stage 1; C: stage 2; D: stage 3. In red there are some examples of matching features. BOTTOM: Full image of the piece Q1 at 10X with a reference square. All images acquired using Sneox 090 100X.

Pedergnana et al., 2016; Martín-Viveros and Ollé, 2020a,b).

Our approach joins other recent works that address the issue of the importance of cleanliness in traceology (Ollé and Vergès, 2008, 2014; Macdonald and Evans, 2014; Pedergnana et al., 2016, 2020; Fernández-Marchena et al., 2018, 2020; Mateo-Lomba et al., 2022). These works recover a part of the methodology that has hardly been addressed since the early years of the discipline and show that the lack of sample preparation is not only an error that can hide traces but can also generate "films" or microlayers that mimic the appearance of the traces themselves (Fernández-Marchena, 2021).

Ultimately, this is a problem that affects the foundations of the analysis itself, but it appears to be much easier to address with an initial analysis using the optical microscope before complementing it with confocal scanning to facilitate the detection of dirt or particles that do not belong to the authentic surface (multianalytical approach). However, as mentioned before, without thorough training in use-wear recognition and residue mimicking traces mistakes can still be made. This is due to the ability to observe a wider focused field of view with metallographic microscopes, as well as better colour capture, which greatly facilitates the differentiation of particles, stains, and traces. It

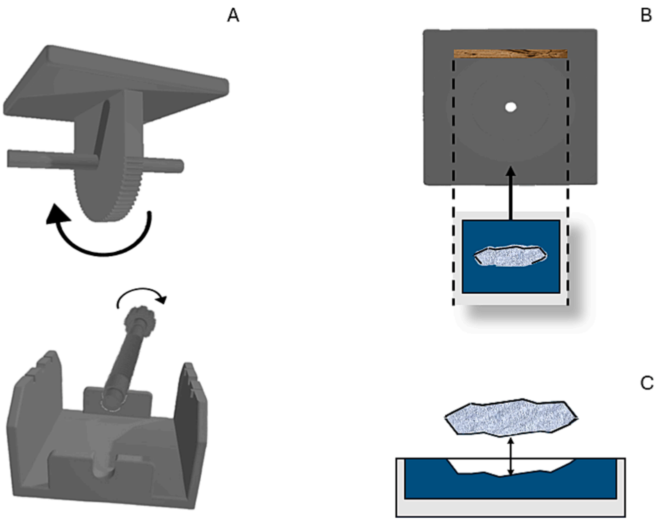

Fig. 5. Schematic representation of the 3D printed gear stage. The original design was modified using *Meshlab* to fit our size requirements. We then incorporated a putty paste mold made from the artifact's negative, secured within a plastic box placed on top, supported by a wooden frame attached to the surface of the platform. The original platform design is from *Left-field Designs.* A: platform structure; B: top view; C: lateral view.

Table 1
Typology and definitions of surface texture parameters used based on international standards (ISO 25178. , 2021).

Type	Parameter	Definition	Type	Parameter	Definition
Height	*Sq*	Root-mean-square height.	Functional Volume	*Vmp*	Peak material volume of the scale-limited surface.
Height	*Sku*	Kurtosis of height distribution.	Functional Volume	*Vmc*	Core material volume of the scale-limited surface.
Height	*Sp*	Max peak height.	Functional Volume	*Vv*	Void Volume.
Height	*Sv*	Max pit height.	Functional Volume	*Vvc*	Core void volume of the scale-limited surface.
Height	*Sz*	Maximum surface height.	Functional Volume	*Vvv*	Pit void volume of the scale limited surface.
Height	*Sa*	Arithmetic mean height.	Functional	*Sxp*	Extreme peak height.
Height	*Smean*	Mean value (surface).	Functional	*Smc*	Inverse areal material ratio.
Height	*Ssk*	Asymmetry.	Functional	*Sk*	Kernel roughness depth (roughness depth of the core).
Spatial	*Sal*	Autocorrelation length.	Functional	*Spk*	Reduced peak height (roughness depth of the peaks).
Spatial	*Str*	Texture-aspect ratio ANISOTROPY.	Functional	*Svk*	Reduced valley depth (roughness depth of the valleys).
Spatial	*Std*	Texture direction.	Functional	*Smr1*	Ratio of the area of the material at the intersection line which separate protruding hills from the core.
Hybrid	*Sdq*	Root-mean square slope gradient.	Functional	*Smr2*	Ratio of the area of the material at the intersection line which separates protruding dales from the core.
Hybrid	*Sdr*	Developed interfacial area ratio –(Indicates the complexity of the surface.)	Functional	*Smr*	Ratio of the area with a specific height c or higher.
Hybrid	*Sratio*	Roughness ratio.	–	–	–

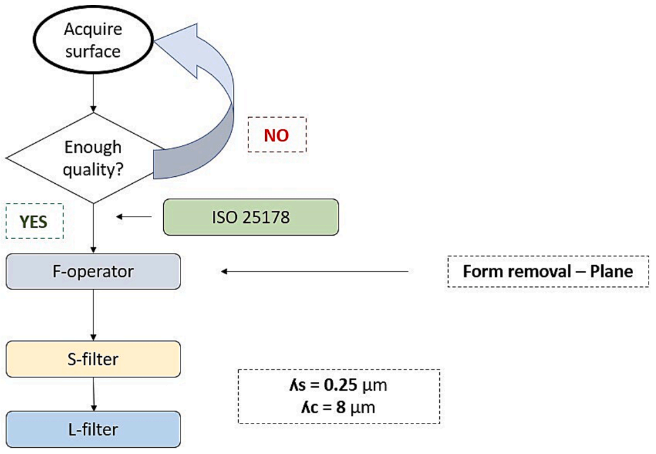

Fig. 6. Roughness variables acquisition workflow.

should be noted that cleaning protocols, not always properly published in use-wear studies (Mateo-Lomba et al., 2022), can make the difference between good results and suspicious results, where sometimes some of the traces shown in the images could potentially be dirt (e.g. Kay and Solecki, 2000; Kay and Mainfort 2014; Berruti and Cura 2016; d'Almeida de Almeida et al., 2023; Berruti et al., 2024; Kappelman et al., 2024).

Overall, numerous studies have been published in recent years using ISO parameters in the lithic use-wear analysis (Stevens et al., 2010; Pedergnana et al., 2020a; Ibáñez and Mazzucco, 2021). It is therefore very important to ensure that the observations we make truly reflect surface characteristics rather than artefacts of surface contamination.

4.1. Methodological limitations

Regarding the possible limitations in terms of reproducibility, Calandra et al. (2019) introduced a newly designed system to ensure reliability in repositioning lithic tools under a confocal microscope during sequenced experimentation. The system used in their study shares similarities with the one employed in our experiment, but there are two main differences between the methodologies.

The first difference is the use of ceramic beads, which they adhered to the ventral side of the samples using either epoxy resin or Paraloid. These beads served as reference points for accurate repositioning. The second difference lies in their use of software to automatically locate a specific position on the sample. Despite this, they manually aligned the position of the first scan acquired with a laser scanning microscope (LSM) to the corresponding position on the second microscope they used (Sneox) to ensure that the surfaces being compared were as similar as possible and that the results were comparable. This suggests that manual repositioning can still be useful, provided the tilt and orientation of the sample are maintained throughout the sequence.

They used a manual goniometer and a silicone mold to hold the samples in place. The silicone mold was made using Provil novo Putty regular set (Kulzer GmbH, Hanau, Germany), a two-component silicone impression material that hardens in 3–5 min at room temperature. This is the same material we employed in our platform (Fig. 5; SI: Figs. 7-9), as other materials, such as plasticine, were found to be too soft, resulting in micrometer-level movements over time. Such instability was sufficient to influence surface acquisition and compromise the results. However, we explored an alternative approach using topographic features such as valleys, edges, or distinctive marks as reference points (see Figs. 3 and 4). This method is less resource-consuming, as well as less invasive, since it avoids introducing new substances to the sample's surface. While ceramic beads may prove highly useful in use-wear sequence experiments—particularly when the beads are positioned centrally, and the sample's edge is subject to modification and study during use—this approach may not always be practical. For example, in studies focused on cleanliness or involving very small samples, the addition of beads may obstruct the process or hide areas of interest. Moreover, for larger pieces with multiple areas of interest that are far apart, manual adjustment may still be required.

Our results demonstrate no statistically significant differences

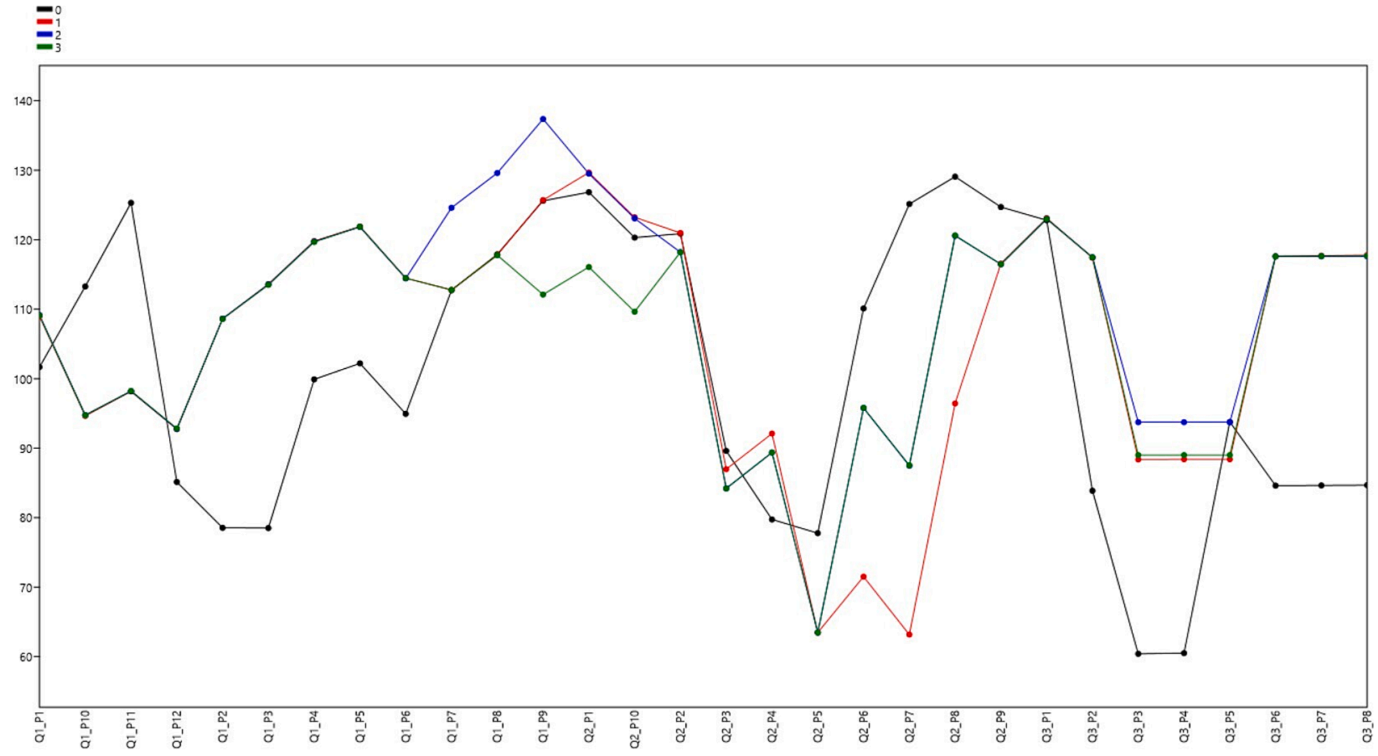

Fig. 7. *Std* values by cleaning stage and point.

Table 2
Friedman test *χ2* statistic and correspondent *pvalue* for every parameter.

Variable	χ2; p	Variable	χ2; p
Sk	Friedman: χ2 = 40,84; p = 7,2035e-09	*Sku*	Friedman: χ2 = 8,72; p = 0,0549
Smc	Friedman: χ2 = 41,2; p = 6,0426e-09	*Smean*	Friedman: χ2 = 27,8; p = 3,2369e-06
Smr	Friedman: χ2 = 15,16; p = 0,0017	*Sp*	Friedman: χ2 = 45,4; p = 7,7587e-10
Smr1	Friedman: χ2 = 42,6; p = 3,0499e-09	*Sq*	Friedman: χ2 = 52,2; p = 2,7732e-11
Smr2	Friedman: χ2 = 31,32; p = 7,3994e-07	*Ssk*	Friedman: χ2 = 27,4; p = 4,9293e-06
Spk	Friedman: χ2 = 59,08; p = 9,4547e-13	*Sv*	Friedman: χ2 = 29; p = 2,2753e-06
Svk	Friedman: χ2 = 49; p = 1,3314e-10	*Sz*	Friedman: χ2 = 54,56; p = 8,7098e-12
Sxp	Friedman: χ2 = 45,52; p = 7,3163e-10	*Sdq*	Friedman: χ2 = 28,17; p = 3,102e-06
Vmc	Friedman: χ2 = 46,13; p = 1,5214e-10	*Sdr*	Friedman: χ2 = 28,59; p = 2,649e-06
Vmp	Friedman: χ2 = 55,48; p = 1,0582e-14	*Sratio*	Friedman: χ2 = 22; p = 1,7866e-05
Vv	Friedman: χ2 = 50,57; p = 2,4007e-11	*Sal*	Friedman: χ2 = 30,16; p = 9,1753e-08
Vvc	Friedman: χ2 = 47,71; p = 7,9804e-11	*Std*	Friedman: χ2 = 0,57; p = 0,85647
Vvv	Friedman: χ2 = 39,16; p = 9,5093e-12	*Str*	Friedman: χ2 = 37,99; p = 8,269e-09
Sa	Friedman: χ2 = 46,72; p = 4,0668e-10	–	–

between Stage 2 and Stage 3 of our experiment, during which no cleaning procedures were performed, and the only intervention was removing and repositioning the sample. This suggests that neither the microscope nor the manual relocation process introduced statistically significant errors, and the statistical differences observed are unrelated to these factors.

While the method proposed by Calandra et al. (2019) is undoubtedly effective, we think it is not the only viable approach and integrating their automated microscope software approach with alternative methods for setting coordinates, could offer a flexible solution in cases where adding external markers is not feasible. Our aim is not to claim that our method is superior but rather to show that, when performed carefully and with sufficient time and attention to detail, it does not interfere significantly with the results. We acknowledge the limitations of manual and qualitative sample repositioning, particularly its time-consuming nature and its susceptibility to human error; however, our findings indicate that these limitations do not compromise the integrity of these results. Therefore, despite the challenges, we chose a manual approach due to the specific requirements of our study and the practical advantages it provided in this context.

In addition, this study focuses on a single raw material, rock crystal, as its surface properties facilitate the identification of dirt better than in chert. However, producing replicas of this work using various materials could provide valuable reference data on the unique characteristics and interactions of each material type with surface dirt. Future investigations could explore material-specific approaches adapted to the unique properties of different substrates, thereby increasing the accuracy and reliability of the results. The inclusion of different cleaning procedures would increase methodological rigour and open up new perspectives. Researchers can establish standardised cleaning protocols that account for material variability and ensure that potential contaminants do not compromise the interpretation of use-wear patterns.

By incorporating a wider range of cleaning methods and materials, the archaeological community can refine existing methods, improve data quality, and strengthen the robustness of interpretations. To achieve these goals, collaboration between experts in archaeology, materials science, and data science is essential. An interdisciplinary approach can lead to the development of innovative cleaning techniques specifically designed for archaeological needs.

Aware of how slow and difficult traceological analysis is in itself, as well as the resources involved in terms of working hours and microscope use, we believe it is necessary to defend once again for the slow science, where published data have all possible analysis guarantees. Although this work aims to show the consequences of not considering the variable

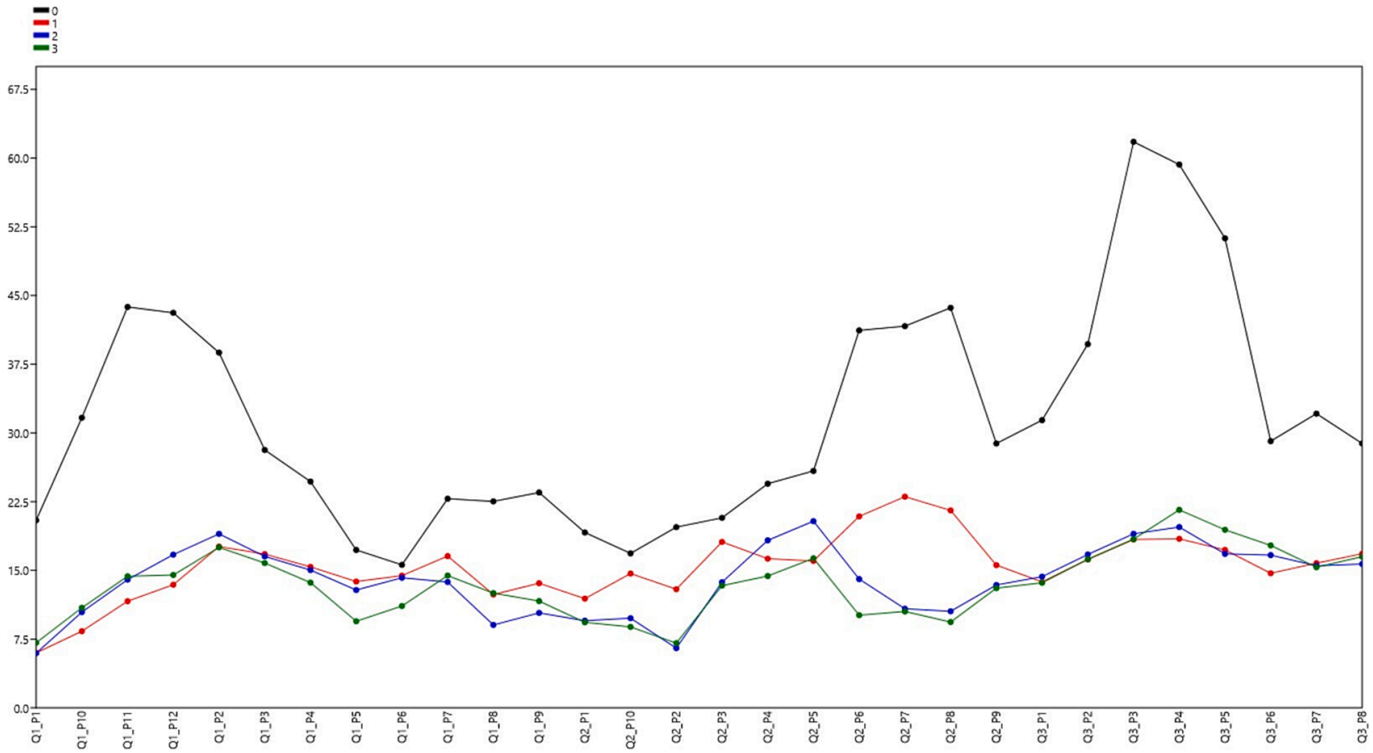

Fig. 8. *Smc* values by cleaning stage and point.

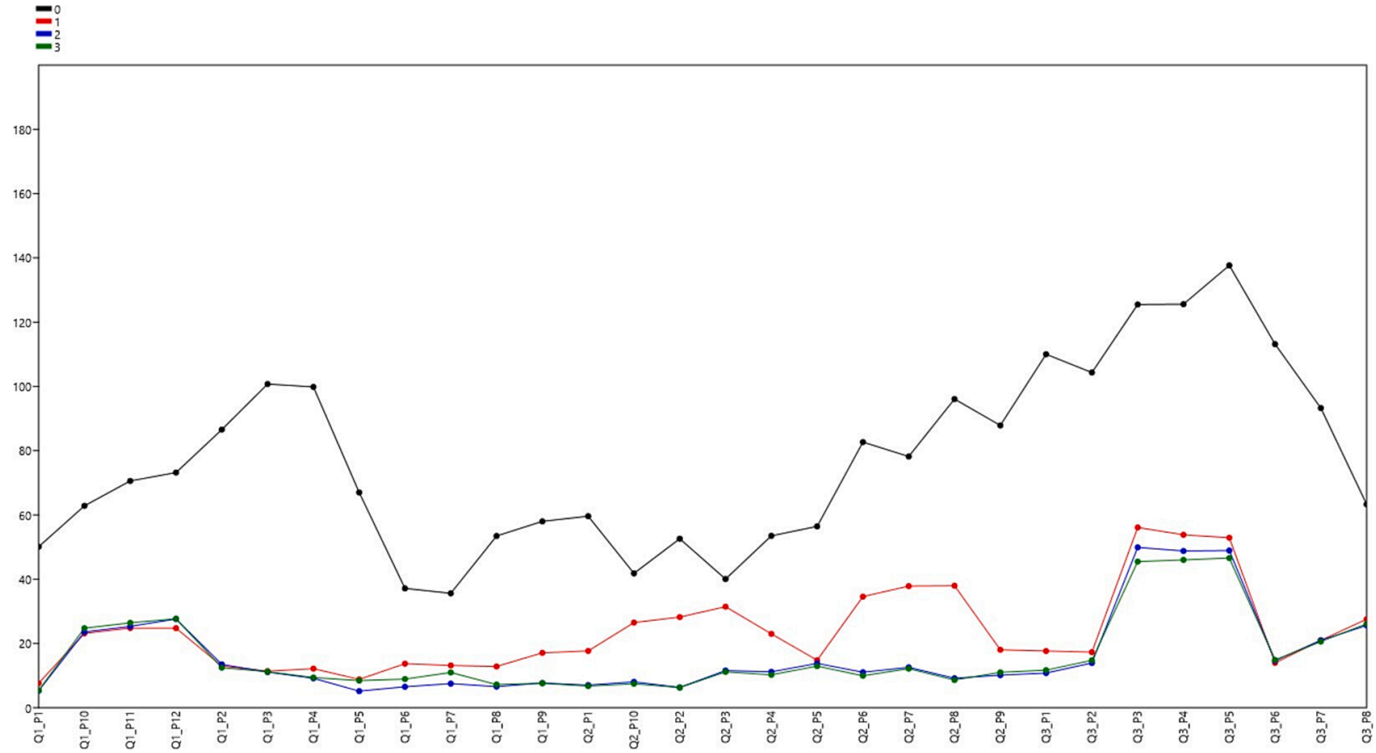

Fig. 9. *Sz* values by cleaning stage and point.

Table 3
Classification of the parameters regarding their dirt sensitivity.

Group 1		Group 2	Group 3
Sa	*Smr2*	*Sp*	*Sku*
Smean	*Vvc*	*Sq*	*Std*
Ssk	*Vv*	*Sv*	
Sal	*Smc*	*Sz*	
Str	*Sk*	*Sxp*	
Sdq	*Smr*	*Spk*	
Sdr	*Smr1*		
Sratio	*Svk*		
Vmc	*Vvv*		
Vmp			

of poor cleanliness in surface quantification, it also highlights the same problem in traditional use-wear analysis, where apparently polished surfaces may actually be simple water or grease droplets. However, attempting to treat quantitative studies in use-wear as a completely unchanging objective system can be a serious mistake if all the methodological steps are not taken into account. In this sense, surface quantification will not distinguish between a clean surface, an extremely dirty one, or one with a thin film of manipulation dirt, and will provide data that is numerically correct, but does not necessarily reflect reality.

5. Conclusions

In conclusion, the results of this study emphasise the critical role of cleanliness in use-wear analysis and quantification of surface roughness parameters, as there are significant differences among cleaning stages, with only two exceptions out of twenty-seven. By categorising these parameters based on their sensitivity to dirt, researchers can make more informed decisions regarding cleaning protocols and data interpretation. However, since this work only focuses on a specific rock crystal sample, additional materials should be tested to determine whether they replicate the results of our study or if sensitivity to surface dirt – whether manipulation residues or soil dirt – is specific to each material.

This work highlights the need for rigorous cleaning procedures as an essential step in ensuring the accuracy and reliability of use-wear analyses.

CRediT authorship contribution statement

Anna Francès-Abellán: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Juan Luis Fernández-Marchena:** Writing – original draft, Conceptualization. **Andreu Ollé:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105121.

Data availability

Data available in the supplementary material.

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