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Quantifying lithic surface alterations using confocal microscopy and its relevance for exploring the Châtelperronian at La Roche-à-Pierrot (Saint-Césaire, France)

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Abstract

Post-depositional modifications or alterations of the surface of lithic artefacts have been characterised at both macroscopic and microscopic scales by means of qualitative criteria. Here we introduce a new methodology for the study of surface alterations based on roughness measurements using confocal microscopy. This new approach allows for a quantified and reproducible distinction between various states of alteration among geological samples and archaeological material from a level attributed to the Châtelperronian at La Roche-à-Pierrot (Saint-Césaire, France). This site, perhaps best known for discovery of Neanderthal remains in a level attributed to the Châtelperronian, plays a critical role in questions concerning the emergence of the Upper Palaeolithic and its relation to the appearance of anatomically modern humans in Western Europe. In this context, the question of the chrono-cultural integrity of the Châtelperronian at Saint-Césaire is crucial. Our results demonstrate considerable variability in surface alterations among a sample of specific artefacts, Châtelperronian points, and those collected in the immediate vicinity of the Neanderthal remains and thus reinforces previous arguments concerning the unreliability of the Neanderthal-Châtelperronian association at Saint-Césaire. This pilot study equally confirms the potential of roughness analysis for both taphonomic and use-wear studies of lithic industries.

Keywords: Confocal microscopy Lithic analysis ; Surface alteration ; Taphonomy ; Roughness measurement ; Châtelperronian Flint ; Saint-Césaire

1. Introduction

Lithic artefacts, although better preserved than organic materials, are subject to multiple types and intensities of surface alterations in sediments after burial. These post-depositional modifications can result from mechanical, chemical, biological or thermic processes (Schiffer, 1987; Texier, 2000) and can be distinguished from wear or damage due to use. Macroscopic surface alterations on archaeological objects, such as white patina, lustre or gloss, were noticed relatively early on in the development of Prehistory (Evans, 1863; Boucher de Perthes, 1864; de Mortillet, 1883; De Puydt, 1885). Today, archaeologists describe alterations evident on lithic artefacts using broad qualitative criteria such as “edge damage” and “rounding”. Surface alterations now form an integral part of prehistoric archaeology and are a common element of techno-economic analyses focusing on assemblage integrity and distinguishing artefacts from geofacts (Bourgon and Bordes, 1951; Peacock, 1991). Considerations of surface modifications equally have applications for determining the preservation of use-related wear (Semenov, 1964; Tringham et al., 1974; Stapert, 1976; Keeley, 1980; Meeks et al., 1982; Plisson, 1985a; Levi Sala, 1986; MansurFranchomme, 1986; Claud, 2008; Asryan et al., 2014; Lemorini et al., 2015), raw material sourcing (Masson, 1981; Demars, 1982; Geneste, 1988; Turq, 1992; Primault, 2003; Fernandes and Raynal, 2006; Fernandes, 2012; Thiry et al., 2014; Delvigne, 2016) and taphonomic approaches evaluating the impact of post-depositional processes on artefacts and the overall integrity of archaeological assemblages (Hiscock, 1985; Villa, 1982; Kaminska et al., 1993; Dibble et al., 1997,

2006; Villa and Soressi, 2000; Bordes, 2002; Burrioni et al., 2002; Eren et al., 2011; Glauber and Thorson, 2012; Gravina et al., 2018).

Regardless the scale of observation, all of the above studies commonly employ qualitative criteria that rely on the experience of each observer. Although this intra- and inter-observer variability is usually evaluated by blind tests, especially in the context of use-wear analyses (for a recent synthesis see Evans, 2014), it can be offset by quantitative studies that assure both the comparability and reproducibility of data. This need for quantitative methods to overcome potential problems with comparability between qualitative analyses is not new (Grace et al., 1985). Recent technological developments in the field of usewear analysis, such as surface textural imagery (Knutsson, 1988; Linton et al., 2016), interferometry (Dumont, 1982; Anderson et al., 2006), atomic force microscopy (Kimball et al., 1995; Faulks et al., 2011) and 3D scanning (Grosman et al., 2011; Benito-Calvo et al., 2017), have helped to better characterize and compare microwear on stone and bone tools. More recently, confocal microscopy has proven to be a successful tool for quantifying use-wear on stone tools (Evans and Donahue, 2008; Evans and Macdonald, 2011; Giusca et al., 2012; Stevens et al., 2010; Stemp and Chung, 2011; Bofill et al., 2013; Stemp et al., 2013, 2017; Evans et al., 2014; Ibáñez et al., 2014a,b, 2016, 2018; Key et al., 2015).

1.1 La Roche-à-Pierrot, Saint-Césaire

With its particular blade and bladelet technology, the Châtelperronian was originally considered a Middle-to-Upper Palaeolithic transitional industry linked with the arrival of anatomically modern humans in Western Europe (Bordes, 1972). However, the discovery of Neanderthal remains associated with Châtelperronian, first at the Grotte du Renne, Arcy-surCure (Leroi-Gourhan, 1958; Bailey and Hublin, 2006) and then at SaintCésaire, considerably changed this vision. Known from France and northern Spain, the Châtelperronian is now recognised as the first genuine Upper Palaeolithic industry in Western Europe and is commonly attributed to the final Neanderthals (d’Errico et al., 1998; Zilhão and d’Errico, 1999; Hublin et al., 2012, 1996; Zilhão, 2006; Ruebens et al., 2015). However, others have questioned the reliability of this association, citing potential problems linked to the stratigraphic integrity of both sites (Bordes, 1981; de Sonneville-Bordes, 1989; Rigaud, 1996; Bar-Yosef and Bordes, 2010; Bordes and Teyssandier, 2011; Gravina et al., 2018).

This site of Saint-Césaire in the Charente-Maritime department of southwestern France is perhaps best known for the 1979 discovery of a partial Neanderthal skeleton in a level (EJOP sup) attributed to the Châtelperronian (Lévêque and Vandermeersch, 1980; Vandermeersch, 1984; Lévêque, 1993). This collapsed rockshelter at the base of an Upper Turonian limestone cliff was discovered during terracing work designed to allow access to mushroom farms in a disused quarry adjacent to the site. This work partially cut through the downslope archaeological deposits. During excavations between 1976 and 1987, Lévêque divided the deposits based almost purely on sedimentological characteristics (e.g. EJOP = *Ensemble jaune orange pale* or pale yelloworange level). The surface alterations of lithic artefacts from the level attributed to the Châtelperronian have previously been described as highly variable (Bachelier, 2011; Soressi, 2011; Gravina et al., 2018), which contrasts with the reported sedimentological homogeneity suggested by Lévêque's description of the deposit. Building on previous methodological work (Caux et al., 2018) and in order to better characterize the variability of surface alterations within this particular deposit and further test its stratigraphic integrity, we applied roughness analysis by means of confocal microscopy to a sample of lithic artefacts from the level (EJOP sup) attributed to the Châtelperronian. Our aim was not, however, to link a particular type of surface alteration to a specific geological process.

Given its importance for debates concerning the Middle-to-Upper Palaeolithic transition in Western Europe, we applied a newly developed quantitative methodology for characterising and comparing surface alterations based on roughness measurements obtained by confocal microscopy. Here we present results from this complementary approach to qualitative descriptions of surface alterations and bring

new quantitative arguments for investigating the integrity of the level containing the Neanderthal skeletal material at La Roche-à-Pierrot, Saint-Césaire.

2. Material and methods

2.1 Geological and experimental samples

We built two reference samples (Table 1) using the same local raw materials described for the archaeological assemblage (Bachelierie, 2011; Soressi, 2011) in order to explore variability in surface alterations within the local environment of the site. The geological sample consists of grey to black Coniacian flint obtained from alterites and colluvial deposits on the plateau immediately above the rockshelter and black Santonian flint collected 3 km west of the site from a primary deposit exposed in a road cut as well as in associated colluvium (Fig. 1).

		Number of objects	Provenance	Number of measured surfaces	
Reference Sample	Geological	20	Alterites	7	14
			Colluvial deposit	13	54
Archaeological sample	Experimental	10	Alterites	5	5
			Colluvial deposit	4	4
			Primary deposit	1	1
			Châtelperronian points	5	8
			Objects from square F5-III	8	19

Table 1. Provenance of objects analysed with confocal microscopy.

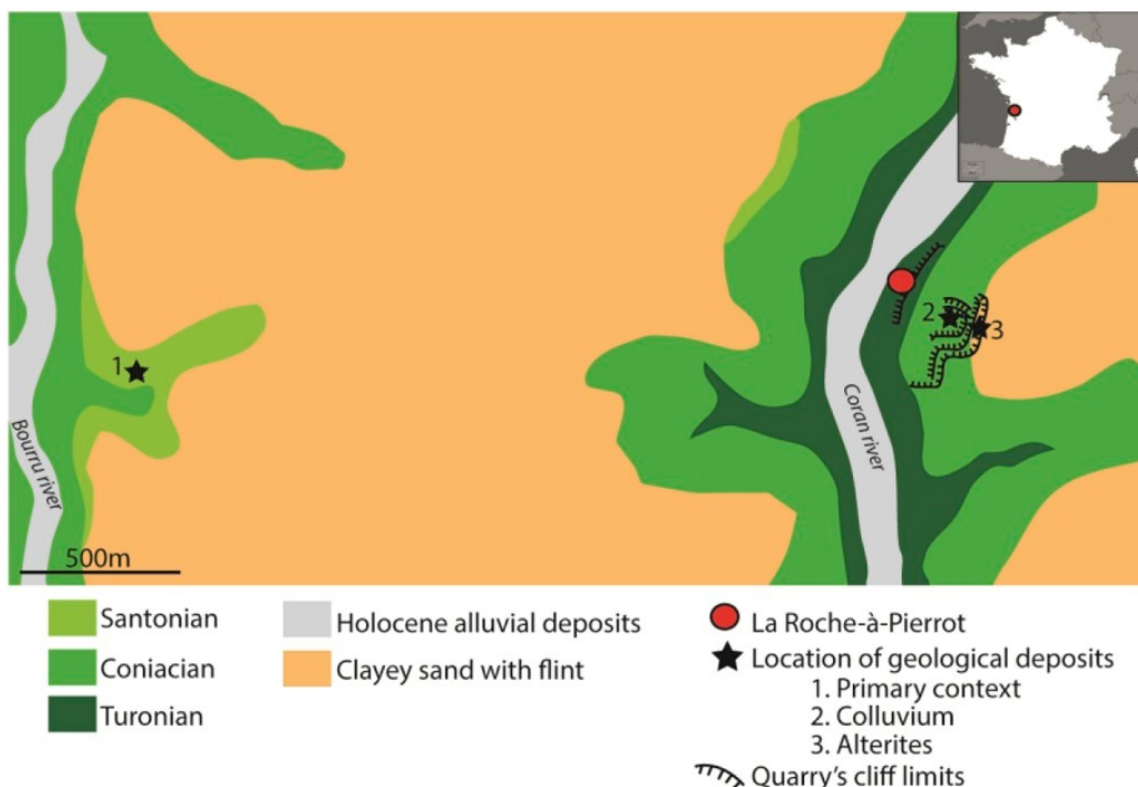
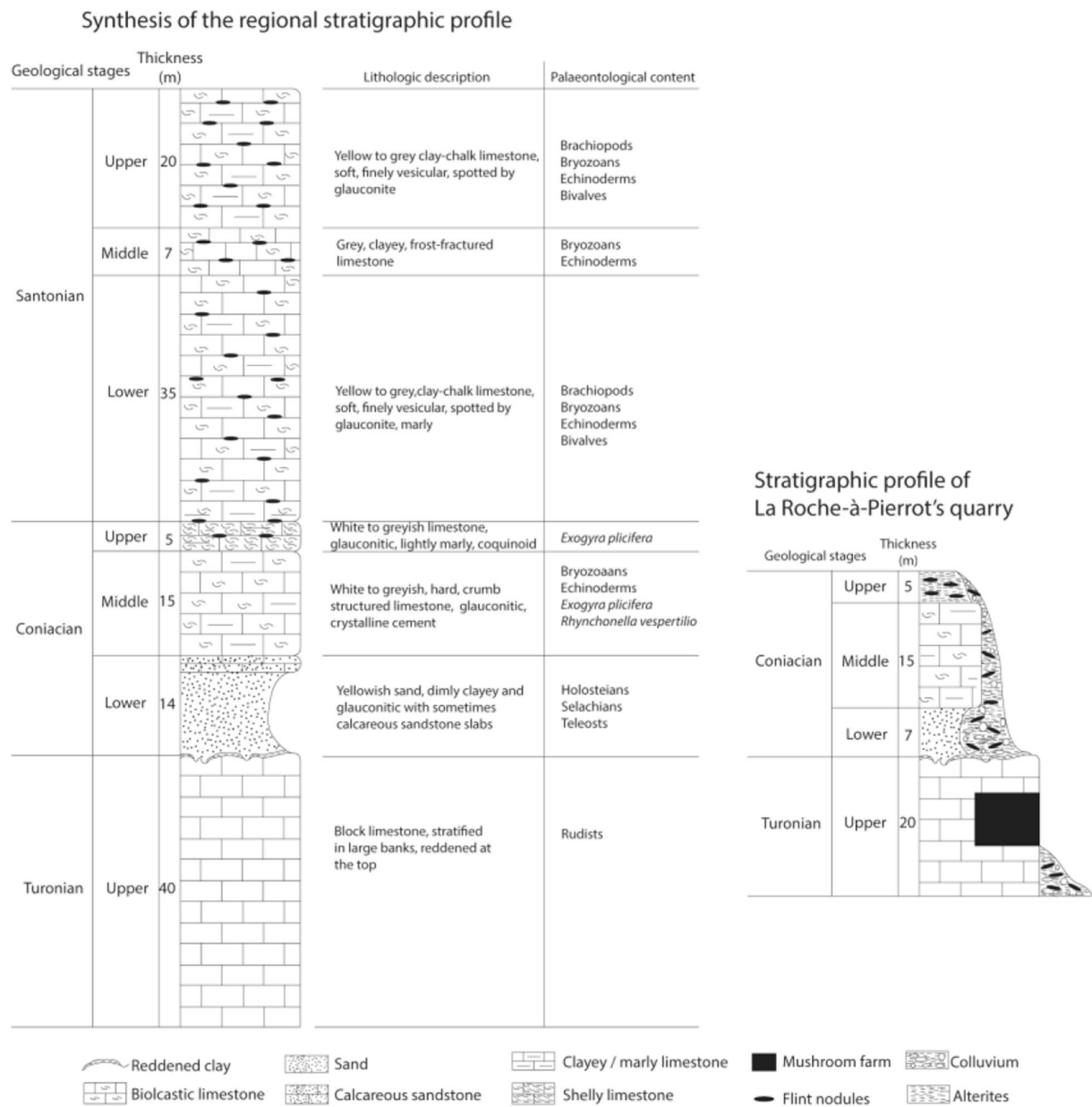


Fig. 1. Simplified geological map of the area around La Roche-à-Pierrot (Bourgueil et al., 1968; Platel et al., 1976)

The plateau immediately overlying the site has been considerably altered by quarrying activity for the extraction of Coniacian and Upper Turonian limestone until the end of the 20th century. This work increased areas of mass wasting and sheet erosion, leading to the formation of colluvial deposits (Fig. 2). Special attention was paid to assembling samples with visibly similar alterations (i.e. lustres and patinas) to what was described for the archaeological material. The geological sample comprises fragments and nodules ranging from 4 to 15 cm in length. The experimental sample included cortical and noncortical flakes detached from blocks or nodules of each flint type (collected from primary, alterites and colluvial deposits) using direct hardhammer percussion and can therefore be considered unaltered by natural processes. These two reference samples allow for a quantified characterization and comparison of surface microtopography before and after exposure to alteration processes.



2.2 The archaeological sample

The archaeological sample comprises 13 artefacts from the level (EJOP) attributed to the Châtelperronian during F.Lévêque's excavations (Table 1). The first group of artefacts is composed of 5 Châtelperronian points, the fossil director of the Châtelperronian (Breuil, 1906), recovered from 5 different squares of the 32 sq. meter excavated area where EJOP and its different stratigraphic subdivisions were identified (see Lévêque, 1993 for details). Three points were recorded in the northeastern part of the site, close to the cliff and about 2 m from the Neanderthal remains. The two others were found in the area where the deposits slope to the southwest, approximately 5 m from the other Châtelperronian points. This subsample therefore allows surface alterations to be characterised amongst what can be considered sub-contemporaneous artefacts. The second group comprises 8 artefacts recovered from a 2 cm spit of a 25 sq. Centimetre sub-square (square F5 - sub-square III) in the immediate vicinity of the Neanderthal remains and therefore allows variability in surface alterations to be explored over a very restricted area. All the selected artefacts are made on Coniacian or Santonian flint identical to the reference sample.

2.3 Confocal analysis

The objects from the reference sample were washed with soapy water and then packed in individual bags. The already washed and marked archaeological material was conditioned in the same way. Although the storage of artefacts has been shown to have an impact on flint surfaces (Plisson, 1985b), this was not taken into account during roughness measurements due to the likelihood of it having only a minimal impact on the overall results, especially as measurements were made away from the edges.

The microtopography measurements and 3D scans of an $877 \times 666 \mu\text{m}$ surface were produced with a Sensofar S neox confocal microscope (Sensofar, Barcelona). Surfaces were scanned with a 20x lens (0.45 NA) allowing a lateral sampling interval of $0.645 \mu\text{m}$, a vertical reproducibility of 8 nm, and an optical resolution of $0.31 \mu\text{m}$. Prior to measurements, surfaces were cleaned with alcohol (90% modified) in order to remove any residues left by the handling of the material. Only surfaces with more than 95% measured points were retained for analysis using the SensoMap 7.2 software package (Sensofar, Barcelona). First, we applied automatic levelling correction using the least-squares plane method, then outliers due to measurement errors were removed and the non-measured points filled with the nearest neighbour algorithm using surrounding valid points. Finally, we separated wavelengths corresponding to roughness from those related to surface form and waviness using a Gaussian filter with a 0.08 mm cut-off, which produced statistically significant differences in roughness values between unaltered flakes and heavily altered surfaces (i.e. white patina). For all samples, 5 to 10 measurements were recorded for each scar negative as natural processes do not uniformly affect objects in respect to their position in the sediment (Fernandes, 2012). Measurements were taken away from the edges in order to avoid confusion with potential use-wear traces (Levi Sala, 1986). The parameters extracted from the roughness area were calculated based on the ISO norm 25178, with each value corresponding to a specific statistical measurement of an area.

Considering the specific goals of this pilot study, a large number of parameters were calculated in order to identify which were most statistically (R software) significant for characterising the variability of surface alterations within the sample. Shapiro-Wilk tests for both unaltered and altered objects demonstrated the majority of parameters are not normally distributed (see Supplementary Material 1). We therefore used a Kruskal-Wallis non-parametric test followed by a posthoc Mann-Whitney test to compare samples from the test group individually (with the Bonferroni correction of the p-values). Firstly, intra-scar homogeneity was tested; P-values for each parameter within each scar were above the 0.05 threshold, and therefore do not reject the hypothesis of uniform alterations within scar negatives. This homogeneity within a single scar negative was used as the basis for comparing scar negatives on the same flake and between samples. Secondly, it can be assumed that the roughness of experimental (or

unaltered) flakes in the same raw material and with homogenous texture should be identical (see Supplementary Material 2). The selected parameters showed significant differences in the degree of alteration between macroscopically different scar negatives in the same flake but also between different objects. Parameters that did not differentiate altered from unaltered surfaces were excluded from the study. In the end, only seven of the 21 tested parameters (Table 2) were retained for the multivariate analyses of the reference collection and the archaeological samples.

Height parameter	Sq	μm	Root mean square height
Material ratio parameters	Smc	μm	Inverse areal material ratio
	Sxp	μm	Peak extreme height
Hybrid parameters	Sdr	%	Developed interfacial area ratio
Functional parameters (volume)	Vv	$\mu\text{m}^3/\mu\text{m}^2$	Void volume
	Vmc	$\mu\text{m}^3/\mu\text{m}^2$	Core material volume
	Vvc	$\mu\text{m}^3/\mu\text{m}^2$	Core void volume

Table 2. Selected roughness parameters (ISO norm 25178).

We used discriminant function analysis to evaluate the impact of the seven parameters for characterizing surfaces. All parameters explain more than 95% of the variance between two cases of macroscopically different scar negatives. This strong correlation justified using only the two best-suited parameters for comparing surface alterations: Sq (root mean square height in μm) and Vvc (core void volume in $\mu\text{m}^3/\mu\text{m}^2$), which characterize, respectively, microtopography and microporosity (Fig. 3).

In all, 649 measurements for the reference sample and 256 measurements for the archaeological sample were obtained. Outlying roughness values were removed using boxplots (Table 3).

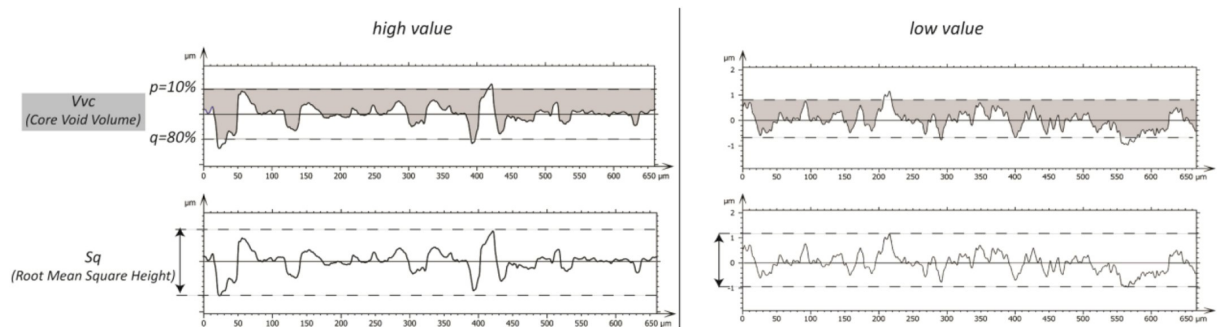


Fig. 3. Description of the two parameters used in the bivariate analyses. High values represent a greater microporosity (Vvc) and higher amplitude in the microtopography (Sq), which can be related to rougher surfaces whereas low values reflect smoother surfaces.

Material provenance	Total number of measurements	Number of removed measurements	% of removed measurements
Santonian flint	433	32	7%
Coniacian flint	268	20	7%
Archaeological sample	268	12	4%
TOTAL	969	64	6%

Table 3. Number and percentage of measurements removed from the study.

3. Results

3.1 The reference samples

Roughness values for the two flint types in the experimental sample overlap, and the Mann and Whitney's test with the Bonferroni correction of the p value does not reject the hypothesis of similarity between the samples (Table 4). We therefore combined the geological and experimental samples for comparisons with the archaeological material.

The discriminant function analysis clearly differentiated two macroscopically distinct alterations on a single object, such as white patina and unaltered surfaces (Fig. 4A), and between those with visibly rougher surfaces (Fig. 4B).

Variability between and within qualitative categories of surface alterations can be measured for multiple objects (Fig. 5). We focused on the three commonly employed qualitative criteria for describing surface alteration: fresh (unaltered), lusted, and white patina. Macroscopically, objects with a white patina often show both high Sq (up to 2.22 μm) and Vvc (up to 2.27 $\mu\text{m}^3/\mu\text{m}^2$) values, which indicates rougher surfaces with higher microporosity. For the lusted samples, the majority of surfaces show lower Sq (between 0.37 and 1 μm) and Vvc values (between 0.42 and 1 $\mu\text{m}^3/\mu\text{m}^2$), meaning smoother surfaces with lower microporosity. The fresh surfaces occupy an intermediate position but have variable roughness values (See Supplementary Material 3). We nevertheless noted several discrepancies between our observations and the confocal measurements; multiple surfaces with white patina showed smooth microtopography and a low microporosity while several lusted objects presented irregular microtopography and a high microporosity (see Supplementary Material 4).

	Santonian flint	Coniacian flint	Geological sample	Châtelperronian points	2 cm spit
Santonian flint		1	3.635E-05	3.247E-06	0.0034
Coniacian flint	1		0.0001751	1.191E-05	0.01675

Table 4. Mann-Whitney pairwise test with Bonferroni corrected p values comparing the experimental sample with the geological and archaeological samples using Sq parameter.

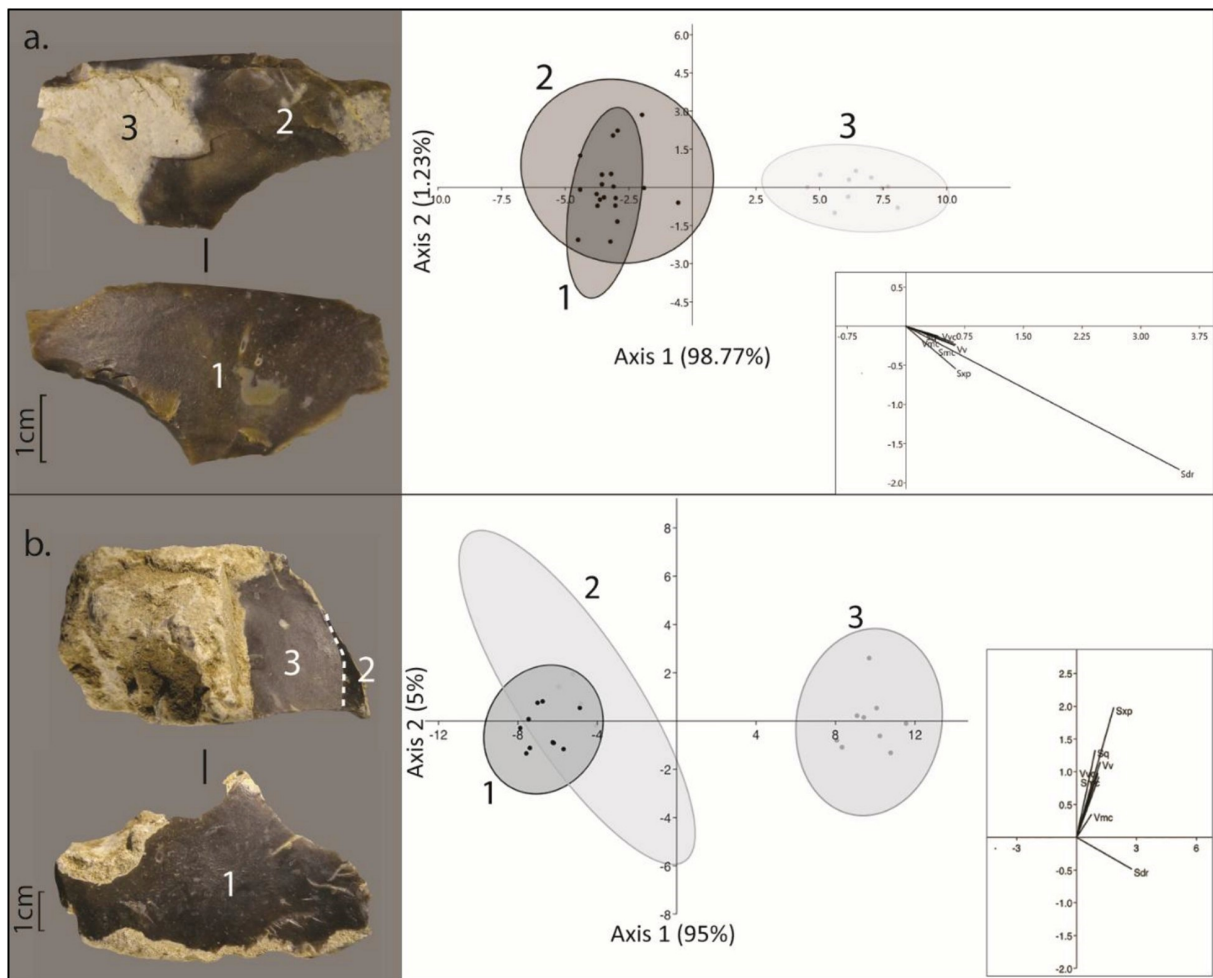


Fig. 4. Discriminant analyses of flakes from the geological sample showing a clear differentiation between altered and unaltered surfaces at macroscopic scale. A. White patina (surface n°3) is clearly distinct from the others surfaces. B. A more matte surface (3) distinct from the other two seemingly unaltered surfaces. The confidence ellipses are set to 95%. In both cases only one axis explains more than 95% of the variance. We can assume that all parameters similarly indicate the difference between scar negatives. Therefore only two of those parameters are taken into account for further analyses.

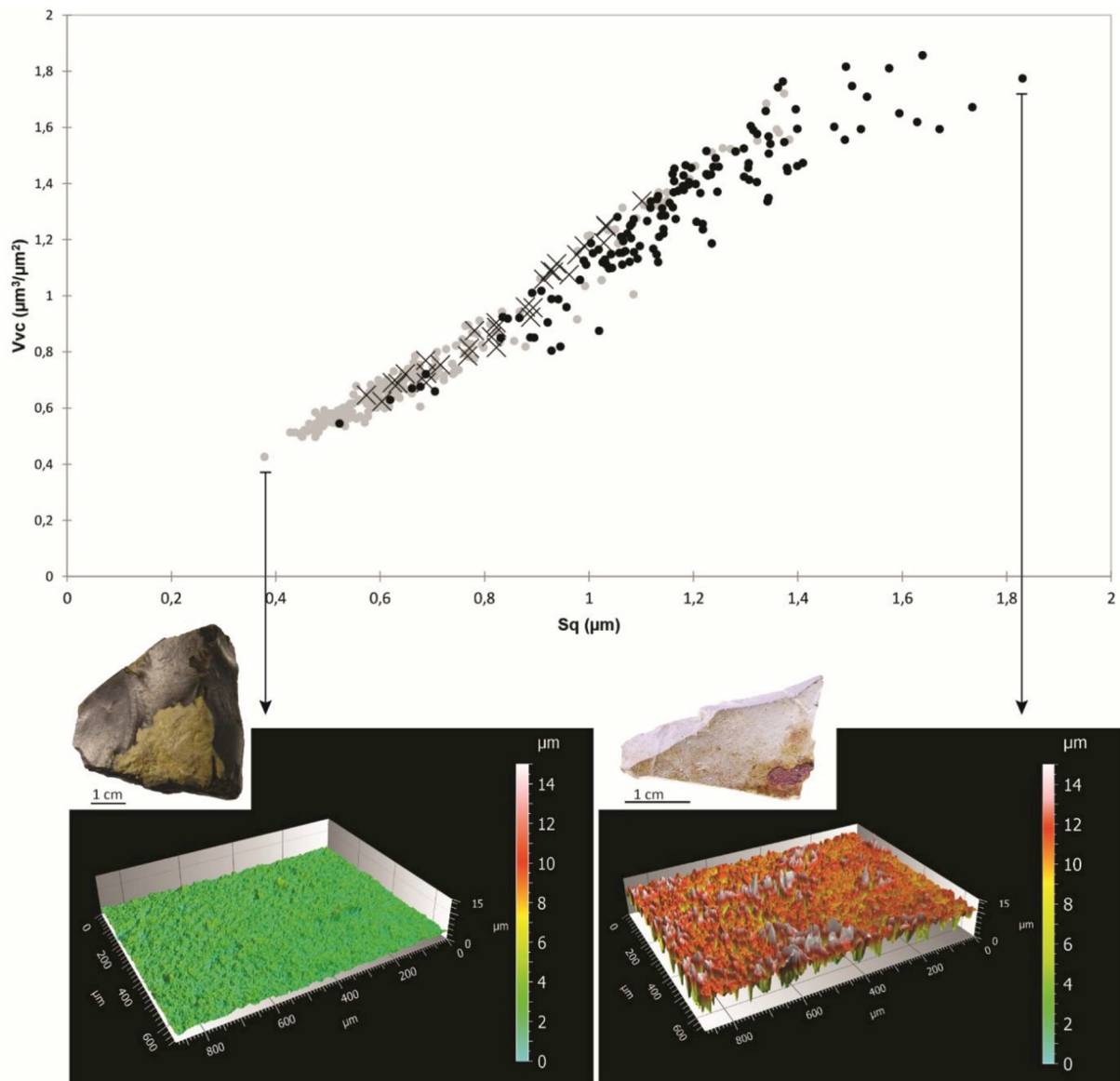


Fig. 5. Bivariate analysis of surface alterations in the reference sample: lustre (light grey points), fresh or unaltered experimental flakes (black crosses) and white patina (black points). Each point corresponds to one measurement. The $877 \times 666 \mu\text{m}$ 3D scans (set up at 15% amplification and 50% resolution) reflects the lowest point (left) on a lustrous surface and (right) the highest roughness value from a surface with white patina. Note the amplitude variations of peak height.

3.2 The archaeological sample

The Châtelperronian points also show clear variability in surface alterations (Fig. 5); two artefacts have white patinas, one is at an advanced stage of desilication, and one is lustred with a white patina. The heavily desilicified Châtelperronian point clearly stands out from the other artefacts given its highly irregular surface microtopography (from 1 to $3.5 \mu\text{m}$) and high surface porosity (from 1.2 to $3.2 \mu\text{m}^3/\mu\text{m}^2$). The point combining lustre and white patina falls within the variability of the points showing lustre only. The remaining artefacts with a macroscopic lustre have low Sq ($0.5\text{--}1 \mu\text{m}$) and Vvc ($0.5\text{--}1.2 \mu\text{m}^3/\mu\text{m}^2$), which is consistent with the geological sample (Fig. 6).

The artefacts recovered from the 2 cm spit are also highly variable in terms of surface roughness ($0.4\text{--}1.5 \mu\text{m}$) and microporosity ($0.5\text{--}1.2 \mu\text{m}^3/\mu\text{m}^2$) (Fig. 7).

Roughness measurements of the geological and archaeological samples clearly overlap (Fig. 8), a pattern strengthened by the Mann and Whitney's test with the Bonferroni correction of the p value that does not reject similarity between samples (Table 5).

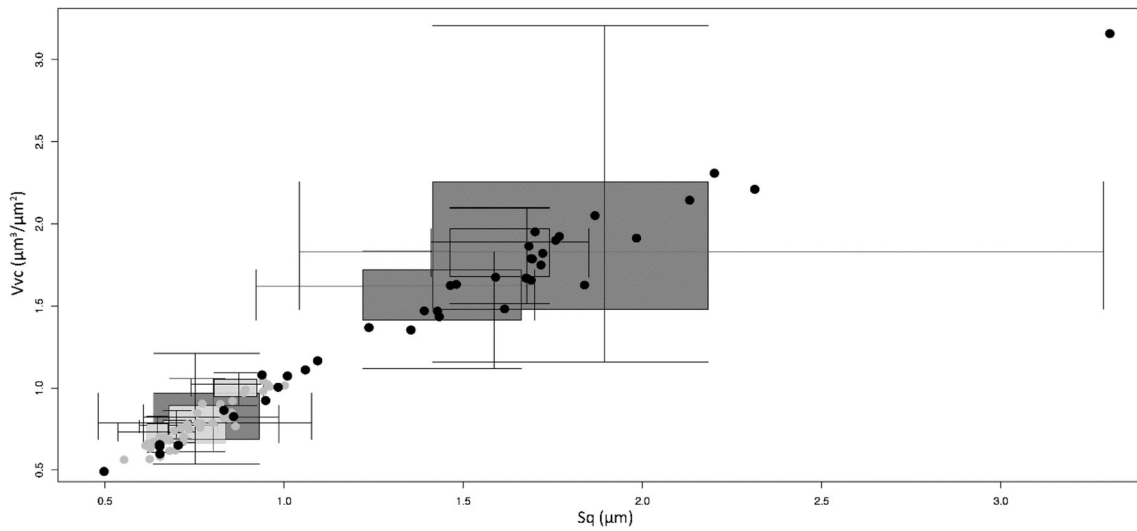


Fig. 6. Roughness values for the Châtelperronian points with white patina (black) and with lustre (light grey). Each boxplot corresponds to a single flake scar. Each point is one measurement.

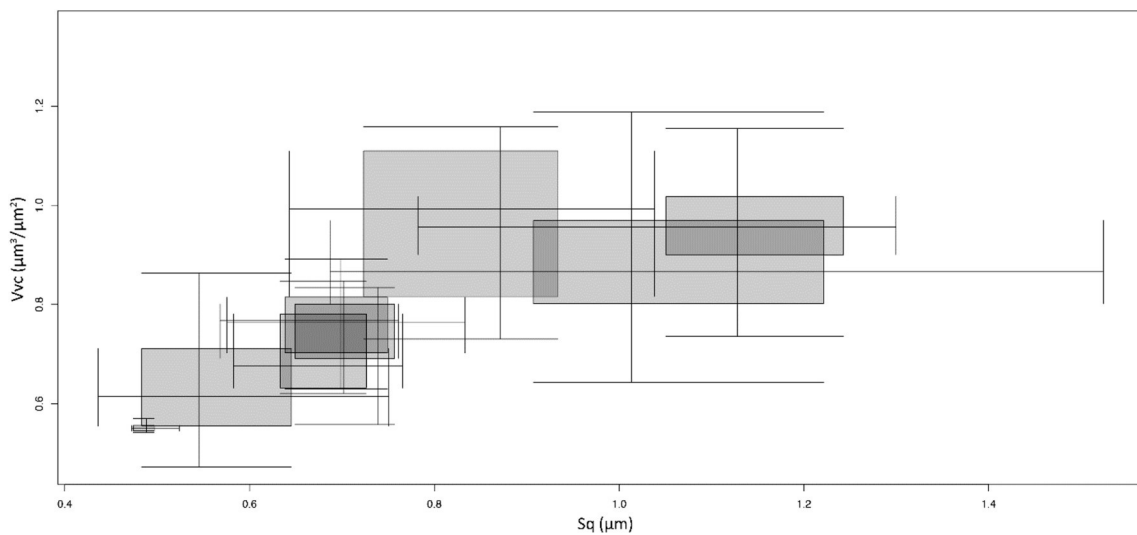


Fig. 7. Archaeological sample from the 2 cm spit of a 25 sq. Centimetre sub-square (square F5 - sub-square III). One boxplot represents one flake scar.

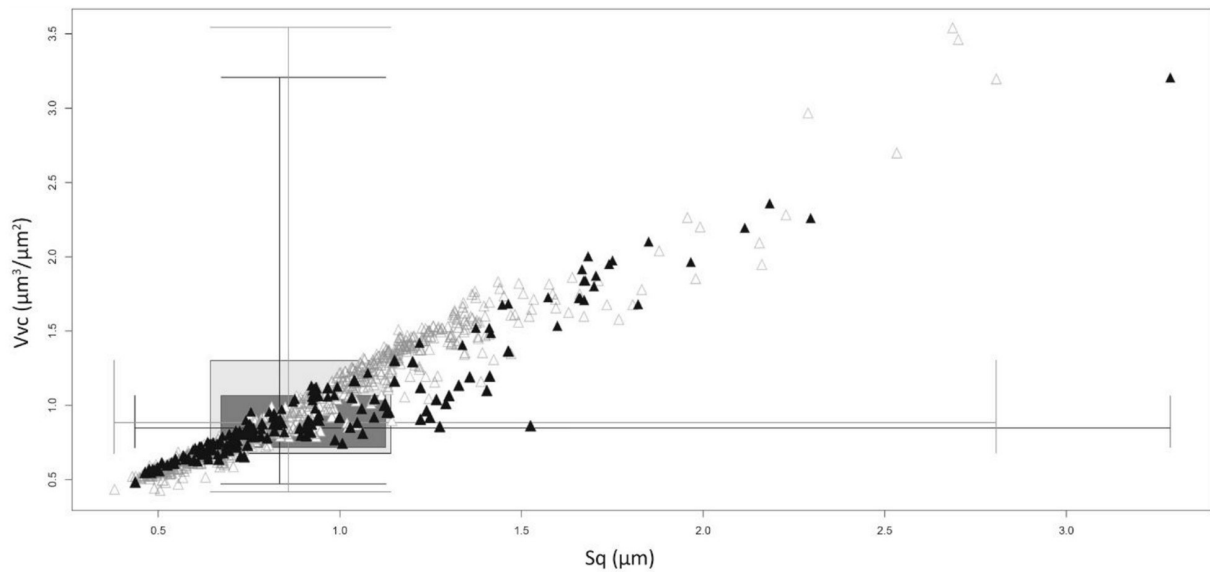


Fig. 8. Bivariate analysis comparing the geological sample (light grey) and archaeological sample (black). Each triangle corresponds to one measurement.

	Geological sample	Châtelperronian points	2 cm spit
Geological sample		0.2279	1
Châtelperronian points	0.2279		0.1164
2 cm spit	1	0.1164	

Table 5. Mann-Whitney pairwise test with Bonferroni corrected p values comparing the geological sample with the archaeological sample using Sq parameter.

4. Discussion

4.1 Characterization of flint microwear

Our analyses confirm that roughness measurements obtained with confocal microscopy can enhance qualitative criteria describing flint surface alterations. First, we demonstrated similarities in roughness values for unaltered flakes detached from blocks of locally available flint (Santonian and Coniacian), a pattern that can be linked to their fine-grained matrices. This allowed us to combine the different raw materials from the geological and archaeological samples into a single, larger group for exploring surface alteration variability in the archaeological sample. Second, clear quantifiable differences exist between extreme states of alteration observed on different scars of a same artefact. Finally, confocal microscopy revealed a continuum of surface roughness when the larger sample and less extreme cases of alteration are taken into consideration. Our results do not always confirm previously reported microscopic observations describing surfaces with white patinas as being irregular with a pitted microtopography (Stapert, 1976; Keeley, 1980) in that they can sometimes be smoother and fall within the variability of lustred surfaces. These differential roughness values can potentially be explained by 1) the subsequent development of lustre homogenising the microtopography and/or 2) the action of mechanical processes abrading and thus flattening the surface. Concerning lustre, despite surface measurements reflecting a general smoothing of the microtopography, some surfaces nevertheless present an irregular and porous microtopography, which is inconsistent with previously reported results and may be explained by 1) a change in soil pH leading to additional chemical attacks (Plisson and Mauger, 1988) or 2) an early stage in the development of lustre. Beyond these distinct cases,

the demonstration of continuous variability in surface alterations should help to improve macroscopic observations by selecting relevant analytical criteria at multiple scales.

The processes responsible for the alteration of lithic surfaces are still widely debated in use-wear analysis, with two main hypotheses advanced to account for their development: the mechanical abrasion of surfaces (Curwen, 1930; Diamond, 1979; Masson et al., 1981; Meeks et al., 1982; Ollé and Vergès, 2008) or the deposit of an amorphous silica gel that fills the hollows of the microtopography (Witthoft, 1967; Keeley, 1980; Anderson-Gerfaud, 1981; Plisson, 1983; MansurFranchomme, 1986; Bradley and Clayton, 1987). Others have proposed surface alterations to be due to combination of these two aspects (Del Bene, 1979; Kamminga, 1979; Unger-Hamilton, 1984). The formation of white patina and lustre involve a broad set of still misunderstood and difficult to reproduce factors (thermic, chemical, mechanical) (Schmalz, 1960; Shepherd, 1972; Rottländer, 1975; Howard, 2002; Glauberman and Thorson, 2012). As the formation of wear is influenced by grain size and morphology (Bradley and Clayton, 1987; Lerner et al., 2007; Fernandes, 2012; Thiry et al., 2014), the use of this protocol should not be limited to fine-grained flint (Caux et al., 2018) but also applied to coarser materials. It can equally be extended to other geological contexts (i.e. alluvial deposits) in order to better characterize variability in surface alterations linked to the depositional environment (Aubry, 1975; Vilas Boas, 1975; Trauth et al., 1978; Masson, 1981; Fernandes, 2012; Sellier and Stephant, 2017).

The equifinality in our reference sample between roughness values of lustre and white patina may be due to localized irregularities in flint microstructure which influences the development of wear (Greiser and Sheets, 1979; Lerner et al., 2007). In this respect, roughness measurements of sequential stages of alteration would help better characterize changes in microtopography. All these considerations should combine multi-scalar qualitative assessments of flint surfaces in order to understand the object as a whole (including edges and ridges). Further work will include tribological analyses in order to better characterize wear processes underlying the formation of surface alterations (i.e. abrasion versus deposition) and to develop a relevant terminology for surface alterations in relation to these wear processes. Other methods

4.2 Interpreting the Saint-Césaire “Châtelperronian”

The lithic industry from the Châtelperronian layer at Saint-Césaire had previously been described as “archaic” due to its substantial Mousterian component (Guilbaud, 1993; Lévêque, 1993), which was advanced as support for a technological and biological continuity between the final Mousterian and the Châtelperronian. However, a recent technological and taphonomic analyses (Gravina et al., 2018) demonstrated the extremely limited quantity of Châtelperronian material mixed with an abundant Middle Palaeolithic component to be the result of post-depositional processes. Our microscopic study of unambiguous Châtelperronian tools and a sample of artefacts from the level containing this material further reinforces this conclusion. Our analysis of what can be considered sub-contemporaneous Châtelperronian points recovered from several different squares of the site indicates that even when two types of alterations are evident (i.e. lustre and white patina), a degree of variability still exists in terms of surface roughness. Additionally, roughness measurements of artefacts from the same spit confirms that the variability of surface alterations of artefacts from a limited volume of sediment is similar to what can be observed in the local environment of the rockshelter. When the whole archaeological sample is taken into account, the distribution of roughness values overlaps with that of the geological sample collected from 3 local geological deposits (primary, colluvial and alterites). These objects show a wide variability of surface alterations within and between each context. The post-depositional modifications of scar negatives show an even wider variability in surface alterations compared to the three geological contexts. Consequently, the archaeological material, including artefacts located near the Neanderthal remains, portrays the same types and degrees of alteration as those documented with flint sampled from the local environment. Variability detected within the 2 cm spit of a 25 sq. Centimetre sub-square argues in favour of the archaeological layer having undergone complex post-depositional processes which remain difficult to distinguish based on a sample from a relatively restricted area. However, the variability of

alterations in this restricted area suggest the artefacts to have been affected by multiple processes rather than a single event resulting in the mass displacement and substantial alteration of artefacts. While surface runoff has been advanced as the main post-depositional phenomena accounting for alterations of the lithic assemblage and the poor preservation of the Neanderthal remains (Rigaud, 1996; Vandermeersch and Hublin, 2007; Bachellerie, 2011), variability of surface alterations documented during our analysis strengthens the likelihood of multiple post-depositional processes affecting this particular layer. For example, periglacial conditions during the period in question would also support the development of solifluction or cryoturbation leading to the movement of objects in the deposits. In addition, the presence of a fissure still visible in the Turonian cliff could have introduced geological and archaeological material from the overlying plateau and be the cause of mechanical damage of artefacts near the cliff, which would explain the fact that two thirds of artefacts greater than 4 cm from EJOP sup have damaged or heavily damaged edges (Gravina et al., 2018). A more detailed understanding of site formation processes based on geoarchaeological analyses will help inform experimental tests designed to evaluate the impact of postdepositional processes on artefacts.

Although time-consuming for an entire archaeological collection, this methodology has the potential to be applied at other sites with complex depositional histories, including the Grotte du Renne at Arcysur-Cure, and can be used to address specific taphonomic issues supported by geoarchaeological data. This type of analysis can also be extended to bone assemblages, particularly dental microwear (e.g. Scott et al., 2005; Ungar and Evans, 2016) and bone tools (Watson and Gleason, 2016).

5. Conclusions

Alongside complementary approaches to the understanding of site formation processes provided by fabric analysis, refitting and spatial projections, the study of surface alterations can benefit from quantitative data obtained with confocal microscopy. Roughness analyses of surface alterations produce a quantifiable and reproducible characterization of alterations undergone by flint artefacts from their geological source to their ultimate archaeological context. This further reinforces the interest of this type of approach versus the discrete classification of samples in different boxes by simple observations with the naked eye. In terms of the broad spectrum of potential surface alterations, roughness measurements clearly separate artefacts with lustred surfaces from those with white patinas. The lithic material from the level attributed to the Châtelperronian during excavations at La Roche-à-Pierrot presents a diversity of surface alterations similar to that recorded in the local environment. The wide variability of alterations resulting from multiple processes acting in this restricted area further highlights the post-depositional reworking of the deposit and reinforces recent doubts concerning the reliability of the Neanderthal-Châtelperronian association at Saint-Césaire based on spatial projections, a techno-typological analysis, and systematic conjoining (Gravina et al., 2018). Future work comparing the preservation of the faunal material with surface alterations of the Neanderthal bones using the methodology outlined here would shed light on their respective post-depositional histories. Although time constraints meant only a limited number of artefacts could be considered in this pilot study, our methodology nevertheless demonstrates the efficiency of confocal microscopy as a new tool for the taphonomic analysis of lithic assemblages.

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Appendix A. Supplementary data

1 **Supplementary Material 1**

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Coniacian flint	Sq (μm)	Vvc ($\mu\text{m}^2/\mu\text{m}^3$)	Santonian flint	Sq (μm)	Vvc ($\mu\text{m}^2/\mu\text{m}^3$)	Experimental sample	Sq (μm)	Vvc ($\mu\text{m}^2/\mu\text{m}^3$)
C_g_1_1	0,013	0,015	S_g_1_1	0,618	0,991	Coniacian_1	0,132	0,289
C_g_1_2	0,010	0,178	S_g_1_2	0,278	0,490	Coniacian_2	0,026	0,009
C_g_1_3	0,600	0,557	S_g_1_3	0,043	0,161	Coniacian_3	0,142	0,448
C_g_2_1	0,776	0,469	S_g_2_1	0,443	0,525	Coniacian_4	0,789	0,633
C_g_2_2	0,998	0,850	S_g_2_2	0,889	0,969	Coniacian_5	0,026	0,002
C_g_2_3	0,171	0,349	S_g_2_3	0,025	0,086	Santonian_1	0,008	0,320
C_g_3_1	0,525	0,385	S_g_3_1	0,865	0,496	Santonian_2	0,577	0,740
C_g_3_2	0,036	0,052	S_g_3_2	0,211	0,133	Santonian_3	0,523	0,001
C_g_3_3	0,902	0,906	S_g_3_3	0,006	0,023	Santonian_4	0,713	0,746
C_g_4_1	0,002	0,004	S_g_4_1	0,542	0,994	Santonian_5	0,149	0,622
C_g_4_2	0,152	0,261	S_g_4_2	0,138	0,169			
C_g_5_1	0,082	0,074	S_g_4_3	0,371	0,291			
C_g_5_2	0,342	0,502	S_g_4_4	0,754	0,240			
C_g_6_1	0,040	0,101	S_g_4_5	0,032	0,025			
C_g_6_2	0,911	0,735	S_g_4_6	0,139	0,041			
C_g_7	0,949	0,404	S_g_4_7	0,086	0,322			
C_g_8	0,226	0,068	S_g_5_1	0,005	0,007			
C_g_9_1	0,416	0,233	S_g_5_2	0,024	0,723			
C_g_9_2	0,904	0,609	S_g_5_3	0,619	0,309			
C_g_9_3	0,995	0,840	S_g_5_4	0,827	0,211			
C_g_10_1	0,992	0,934	S_g_5_5	0,837	0,579			
C_g_10_2	0,531	0,124	S_g_5_6	0,342	0,173			
C_g_10_3	0,015	0,007	S_g_5_7	0,902	0,947			
C_g_11_1	0,502	0,905	S_g_5_8	0,438	0,164			
C_g_11_2	0,862	0,748	S_g_6_1	0,123	0,591			
C_g_11_3	0,611	0,107	S_g_6_2	0,845	0,665			
			S_g_6_3	0,870	0,939			
			S_g_7_1	0,055	0,031			
			S_g_7_2	0,658	0,789			
			S_g_7_3	0,047	0,047			
			S_g_7_4	0,734	0,765			
			S_g_7_5	0,067	0,012			
			S_g_7_6	0,176	0,346			
			S_g_7_7	0,986	0,832			
			S_g_8_1	0,111	0,598			
			S_g_8_2	0,841	0,065			
			S_g_8_3	0,001	0,001			
			S_g_8_4	0,980	0,331			
			S_g_8_5	0,434	0,203			
			S_g_8_6	0,027	0,036			
			S_g_9_1	0,387	0,351			
			S_g_9_2	0,662	0,620			
			S_g_9_3	0,309	0,700			

3 *Shapiro-Wilk tests for both the geological sample (coniacian and santonian flint) and the experimental / unaltered sample*
 4 *using Sq and Vvc. The values that do not follow the normal law of distribution are in bold character.*

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8 **Supplementary Material 2:**

Sq (μm)	C_1	C_2	C_3	C_4	C_5	S_1	S_2	S_3	S_4	S_5
C_1	1	1,000	0,972	1,000	1,000	1,000	0,225	0,999	0,130	0,510
C_2	1,000	1	0,982	1,000	1,000	1,000	0,815	1,000	0,088	0,916
C_3	0,972	0,982	1	1,000	1,000	0,724	0,673	0,999	0,100	0,996
C_4	1,000	1,000	1,000	1	1,000	0,989	0,307	1,000	0,103	0,972
C_5	1,000	1,000	1,000	1,000	1	1,000	0,565	1,000	0,159	0,854
S_1	1,000	1,000	0,724	0,989	1,000	1	0,159	0,972	0,455	0,225
S_2	0,225	0,815	0,673	0,307	0,565	0,159	1	0,404	0,072	0,916
S_3	0,999	1,000	0,999	1,000	1,000	0,972	0,404	1	0,132	0,993
S_4	0,130	0,088	0,100	0,103	0,159	0,455	0,072	0,132	1	0,732
S_5	0,510	0,916	0,996	0,972	0,854	0,225	0,916	0,993	0,732	1

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Vvc ($\mu\text{m}^2/\mu\text{m}^3$)	C_1	C_2	C_3	C_4	C_5	S_1	S_2	S_3	S_4	S_5
C_1	1	0,996	0,996	0,982	1,000	0,190	1,000	0,510	0,057	0,982
C_2	0,996	1	0,939	0,916	1,000	0,815	0,982	0,888	0,108	0,939
C_3	0,996	0,939	1	1,000	0,993	0,282	1,000	0,225	0,170	1,000
C_4	0,982	0,916	1,000	1	0,958	0,282	1,000	0,159	0,170	1,000
C_5	1,000	1,000	0,993	0,958	1	0,854	0,972	0,888	0,264	0,939
S_1	0,190	0,815	0,282	0,282	0,854	1	0,132	1,000	0,565	0,280
S_2	1,000	0,982	1,000	1,000	0,972	0,132	1	0,404	0,280	1,000
S_3	0,510	0,888	0,225	0,159	0,888	1,000	0,404	1	0,916	0,190
S_4	0,057	0,108	0,170	0,170	0,264	0,565	0,280	0,916	1	0,105
S_5	0,982	0,939	1,000	1,000	0,939	0,280	1,000	0,190	0,105	1

10 *Kruskal-Wallis tests for the experimental sample using Sq and Vvc. C stands for Coniacian flint, S for Santonian flint. The*
 11 *homogeneity between the roughness values of the experimental (unaltered) sample is accepted.*

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16 **Supplementary Material 3:**

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	Fresh (experimental)	White patina	Lustre
Mean	SQ	0.890	1.037
	VVC	0.934	1.140
Median	SQ	0.795	1.065
	VVC	0.815	1.163

Standard deviation	SQ	0.339	0.327	0.194
	VVC	0.432	0.389	0.236

20 *Measures of central tendency for the reference sample according to the three qualitative categories of surface alterations.*

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Supplementary Material 4:

	Qualitative categories	Roughness measurements		
		General mean of the corresponding category	Artifact mean	
			Sq	Vvc
Alterites n°1			0.865	0.842
Colluvium n°1	White patina	1.037	0.733	0.710
Colluvium n°2			0.595	0.555
Alterites n°2			1.191	1.417
Colluvium n°3	Lustre	0.689	1.106	1.314

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Artifacts showing discrepancies between the qualitative categories and the roughness measurements.