Quaternary International xxx (2016) 1–17

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy

Andreu Ollé [a, b, *], Antonella Pedergnana [a, b], Juan Luis Fernández-Marchena [a, b, c], Sabine Martin [d], Antony Borel [e], Victoria Aranda [a, f]

[a] IPHES, Institut Català de Paleoecologia Humana i Evolució Social, Zona educacional 4, Campus Sescelades URV (Edifici W3), 43007, Tarragona, Spain
[b] Àrea de Prehistòria, Universitat Rovira i Virgili, Fac. de Lletres, Av. Catalunya 35, 43002, Tarragona, Spain
[c] SERP, Dept. Prehistòria, H. Antiga i Arqueologia, Fac.de Geografia i Història, Universitat de Barcelona, c/Montalegre 6-8, 08001, Barcelona, Spain
[d] Department of Archaeology, University of Exeter, Laver Building, North Park Road, Exeter, EX4 4QE, United Kingdom
[e] Département de Préhistoire, Muséum national d'Histoire naturelle, UMR 7194-CNRS, 1 rue René Panhard, 75013, Paris, France
[f] Equipo de Investigación Primeros Pobladores de Extremadura, Casa de Cultura "Rodríguez Moñino", Avda. de Cervantes, s/n, 10005, Cáceres, Spain

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Use-wear analysis
Experimental archaeology
Quartz
Quartzite
Rock crystal
Microscopy

ABSTRACT

In general, quartz and most of non-flint rocks have not been extensively studied from a functional point of view. Very frequently the definitions of micro-features connected with flint surfaces have been used to describe those encountered on non-flint tools. This circumstance has repeatedly posed serious methodological problems for evaluating the accuracy of functional results when analysing use-wear on quartz and quartzite implements. This is due to the intrinsic divergences in morphology and distribution of use-wear with regard to the different lithic raw materials.

Even though important efforts to systematise use-wear features on quartz have been done almost since the beginning of the discipline, there continues to be confusion and lack of standardisation regarding terminology in this aspect.

In this paper, we try to contribute to new insights in this research by means of selecting examples from an extensive experimental programme involving different raw materials: from rock crystal (the purest form of quartz found in nature) to vein quartz and quartzite, with the latter two materials extensively used for knapping throughout Prehistory and still poorly understood in terms of microwear. For data recording, we preferentially used sequential experiments and resorted to both Optical Light and Scanning Electron Microscopy.

We focused our interest on describing the main groups of wear features. The results obtained allowed us to assess the different mechanical behaviours under the stressors induced by tool-use from a group of raw materials with the same chemical composition but very different in structure. Furthermore, we propose the revision of some terms commonly employed when documenting micro-wear on quartz and similar rocks, as well as recurring concepts coming from materials and geological sciences (e.g. tribology, quartz exoscopy...).

1. Introduction

Use-wear studies of non-flint/chert raw materials have not been sufficiently developed in the past and for this reason functional interpretation of such materials is still problematic. This relies on the fact that analysts concentrated their efforts in analysing assemblages mainly composed by flint or chert (generically referred thereafter as chert), because of the feasibility of these material to the easy observation of wear with light microscopy. Therefore, based on wide reference collections, analysts came to broadly know the specific use-wear patterns connected with different actions and worked materials contributing to the creation of a solid methodology (e.g.Semenov, 1964; Tringham et al., 1974; Keeley, 1980; Vaughan, 1985; Van Gijn, 1990).

Most attention is presently paid to the improvement of the technological studies of assemblages composed by quartzose materials (quartz and quartzite), as demonstrated by the contributions to this volume. To join this increasing interest in those materials, it

* Corresponding author. IPHES, Institut Català de Paleoecologia Humana i Evolució Social, Zona educacional 4, Campus Sescelades URV (Edifici W3), 43007, Tarragona, Spain.
E-mail addresses: aolle@iphes.cat, andreu.olle@urv.cat (A. Ollé).

http://dx.doi.org/10.1016/j.quaint.2016.02.005
1040-6182/

is worth reviewing their role within the history of lithic use-wear analysis, and evaluating the methodological problems connected with detecting use-wear on them. For instance, previous studies (e.g. Grace, 1990; Igreja, 2009; Borel et al., 2014) have discussed the difficulty of microscopically analysing coarse materials, such as quartz, quartzite and basalt (as well as for other rocks including coarse particles of other minerals). This can be explained sometimes by the high reflectivity and the resulting bright diffraction halo of the rocks analysed (quartz, quartzite, rock crystal or hyaline quartz) and sometimes by the great irregularity of the flaked surfaces (sandstone, quartzite, basalt, rhyolite). However, a paradox on the suitability of use-wear analysis of quartz using the standard high-power method, especially when post-depositional processes affect the lithic assemblages, has been highlighted (Knutsson, 1988b:122).

At the same time, when definite circumstances promoted the functional study of non-chert raw materials, very extensive and complete methodologies have been constructed (Knutsson, 1988a; Knutsson et al., 1988; Richards, 1988; Sussman, 1988; Hurcombe, 1992; Clemente-Conte, 1995/2008). Usually, this occurred when the great abundance of these types of rocks in some regions was largely reflected in the archaeological lithic assemblages coming from those regions (e.g. Kamminga, 1982; Knutsson, 1988b; Derndarsky, 2009; Eigeland, 2009; Kononenko, 2011). Although based on very in-depth investigations, those contributions alone were not enough to establish a universally recognised method to perform use-wear analysis of those materials. In some cases (Knutsson, 1988a) a very thorough description was presented, combining specific traces with relative actions and worked material, which resulted in very useful comparative tables. Of course, the fact that the method did not reach a general acknowledgement has nothing to do with the quality of the method as such, but with the fact that, in this case, quartz hardly gained the interest of use-wear analysts.

Often the analyses of those materials required procedures to overcome the methodological limitations posed by the classical microscopic analysis, which is based on the reflected light observation. Other microscopic techniques have been employed to improve the potential of use-wear analysis on non-flint materials. Among these techniques, the Scanning Electron Microscope (SEM) revealed to be very useful for imaging purposes from almost the beginning of the discipline (Borel et al., 2014; Ollé and Vergès, 2014, and references therein), and, more recently, the Laser Scanning Confocal Microscope (LSCM) ushered a really promising progress in terms of wear quantification (Derndarsky and Ocklind, 2001; Evans and Donahue, 2008; Stemp et al., 2013; Ibáñez et al., 2014).

Moreover, terminological confusion introduced new problems in an already complicated discipline predominantly dependant on the personal experience of the analyst (Grace, 1996). In fact, very frequently different terms were employed to define the same use-wear trait or sometimes the same term was used to describe different traces. Also, direct analogies between traces found on chert and non-chert implements were made, underestimating the fact that use-wear develops differently on distinct raw materials (Greiser and Sheets, 1979; Clemente-Conte, 1995/2008, 2015; Lerner et al., 2007; Clemente and Igreja, 2009).

Quartzose materials were extensively used in the knapping activity in Prehistory and so it would be desirable to improve use-wear analyses on them. Beside, these materials tend to present better preservation conditions than chert, for example, which is more resistant to post-depositional processes (Knutsson, 1988b). Actually, sometimes use-wear analysts are not able to analyse chert artefacts because of the presence of strong patinas or desilicification processes. This is one of the reasons why we initiated an extensive experimental programme aimed to monitor use-wear formation on lithologies with a very similar basic chemical composition (vein quartz, rock crystal and quartzite). All of those materials are formed by macrocrystalline quartz crystals, but their structures are very different (grain size, flatness, etc.). This programme is currently being built to assist the study of the archaeological materials from the following Palaeolithic sites: Gran Dolina-TD10, Burgos, Spain (Ollé et al., 2013), Santa Ana, Cáceres, Spain (Carbonell et al., 2005), Payre, Ardèche, France (Moncel et al., 2008) and Cova Eirós, Lugo, Spain (Rodríguez et al., 2011).

The main aims of the current project are to assess the degree to which inter-rocks variability among quartzose materials affects use-wear formation and development and also to assess the point at which they present a similar use-wear pattern. For this reason, we highlight the need to precisely and independently describe the main groups of use-wear features on each lithology, to then later compare them. In parallel to the general description of the use-wear patterns associated to each raw material, we consider some propositions on terminological aspects to describe use-wear on quartzose raw materials.

Additionally, we explore the advantages and disadvantages of different microscopic techniques in relation to each of the materials taken into consideration. In fact, the type of microscopic equipment employed to perform functional studies, and the specific expertise of the analysts in doing it, might influence the description of use-wear to some degree. For example, use-wear traits are imaged differently depending on the employed microscope and analysis conditions, and also some traces may or may not be detectable depending on the resolution reached by each observation technique and settings chosen.

2. Materials and methods

2.1. Experimental programme

Experiments and results shown here do not take part of an *ad hoc* programme, but derive from different recent or still ongoing programmes aimed to furnish the needed reference collections to interpret the results obtained in the aforementioned archaeological sites (Ollé, 2003; Martin, 2012; Fernández-Marchena, 2013; Aranda et al., 2014; Pedergnana and Ollé, 2014; Fernández-Marchena and Ollé, 2016; Pedergnana and Ollé, 2016; Pedergnana et al., 2016). All these experimental programmes share the use of different quartzose materials, from different varieties of quartzite to vein quartz and rock crystal. Although these programmes include traditional, controlled and sequential experiments (Ollé and Vergès, 2014), we especially selected examples of the latter type, as they allow the subsequent phases of surface modification to be monitored and the evolution of the micro-relief to be precisely tracked throughout the course of the activity performed.

The monitoring of the wear process was especially interesting in this context because we did not aim to offer a catalogue of wear traces, but to learn how the main wear features originate and evolve on the selected materials after having performed similar actions. In other words, we study the mechanism of wear formation from the progressive development of a worn surface, tracing its progressive modification at single points throughout the use process.

The detailed procedures and general advantages of such sequential experiments have been recently discussed (Ollé and Vergès, 2014). In short, we systematically record the development of use-wear traces at several points in order to document the variability of the effects of a given action on the active edge of a tool as closely as possible. Thus, the experimental tools were analysed before use and then at specific intervals during their use.

2.2. Microscopic analysis

The results presented in this study were obtained by the combined use of optical light and scanning electron microscopes, as these demonstrated to be very complementary techniques (Borel et al., 2014) (Fig. 1). The low magnification approach based on stereomicroscope analyses was only followed for sample screening and location of points of interest.

The Zeiss Axioscope A1 reflected light microscope was used with the differential interference contrast (DIC) system, in which Nomarski prisms confers a 3D-like look to the image, as it has been proved to be suitable for the analysis of transparent and birefringent materials (e.g. Pignat and Plisson, 2000; Igreja, 2009; Fernández-Marchena and Ollé, 2016; Márquez et al., 2016). Here the images were taken with a motorised extended focus system. SEM microscopes were used as shown in previous articles (Ollé and Vergès, 2008, 2014; Borel et al., 2014). Table 1 shows the specific details of the equipment used.

Although initially we planned to carry out the analyses equally combining both optical and electron microscopes in all the materials, we have only extensively the former for the rock crystal while milky quartz and quartzite were more extensively documented under the SEM. This directly stems from the grain size, texture and irregularity of these raw materials, as will be further discussed below.

Although in just an exploratory way, and without any quantification approach so far, we occasionally added the confocal laser scanning to the imaging techniques used, with the aim to get insight on some specific details of the wear process of these materials (see Fig. 9).

3. Results

In this section we grouped the main wear features into the following big groups: edge fracturing, linear features and polish. For each of these essential categories of features we comment on a

Table 1
Specifications of the OLM and the two SEM used during this study. EC = Enhanced Contrast objectives; DIC = Differential Interference Contrast; LD = Long Distance.

Optical Light Microscope (OLM)				
Brand and model	Zeiss Axio Scope A1			
Lineup description	Stand column Axio Scope Vario, 560 mm			
	Upper stand part M27 – HD/FL reflected-light illumination for HAL 100			
	4 positions reflector turret			
	Binocular phototube 30°/23 (5:50)			
	100 W halogen illuminator with collector			
	Stop slider A 14 × 40 mm with aperture stop			
	Stop slider A 14 × 40 mm with luminous-field diaphragm			
	Stop slider C-DIC 6x60 EC LD EPN 20×- 50×			
	Polarizer slider A 6 × 30 mm, 90° rotable			
	Analyzer slider D/A, fixed			
	Reflector module brightfield ACR P&C for reflected light			
	Reflector module darkfield ACR P&C for reflected light			
	Reflector C-DIC for reflected light			
	Z motor controler Prior ES10ZE			
	Z focus motor H112			
Objectives				
Model	EC epiplan 5×	EC epiplan 10x	LD epiplan Noefluar 20x HD DIC	LD epiplan Neofluar 50x HD DIC
Model number	422030-9901	422040-9901	422852-9960	442855-0000
Numerical aperture (na)	0.13	0.2	0.4	0.5
Working distance (wd) in mm	16.1	16.1	7.1	6.5
Field of view (fov) in mm	23	23	20	20
Magnification range Eyepieces	50× to 500×			
Oculars	PL 10×/23			
Camera				
Brand and model	Invenio 5S vII			
Resolution	5 Megapixels			
Adapter	CCD adapter 1x			
Software	DeltaPix Insight			
Scanning Electron Microscopes (SEM)				
Brand and model	JEOL JSM-6400			
Detectors	Secondary electron Everhart-Thornley detector (ETD)			
	Back-scattered electron detector (DualBSD)			
	EDX-EXL II system Link Analytical Oxford			
Beam energy set up	15/20 kv			
Working distance used	Between 15 and 20 mm			
Captured image resolution	1024 × 832 pixels			
Software	Oxford Instruments, INCA suite v.4.01			
Brand and model	FEI Quanta 600			
Detectors	Secondary electron Everhart-Thornley detector (ETD) when working at high vacuum			
	Large Field detector (LFD) when working at low vacuum			
	Back-scattered electron detector (DualBSD) for both high and low vacuum			
	EDX-EXL II system Link Analytical Oxford			
Beam energy set up	20 kv			
Working distance used	Between 8 and 18 mm			
Captured image resolution	Up to 4096 × 3536 pixels (used resolution: 1024 × 943 pixels)			
Software	Oxford Instruments, INCA suite v.4.01			

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005

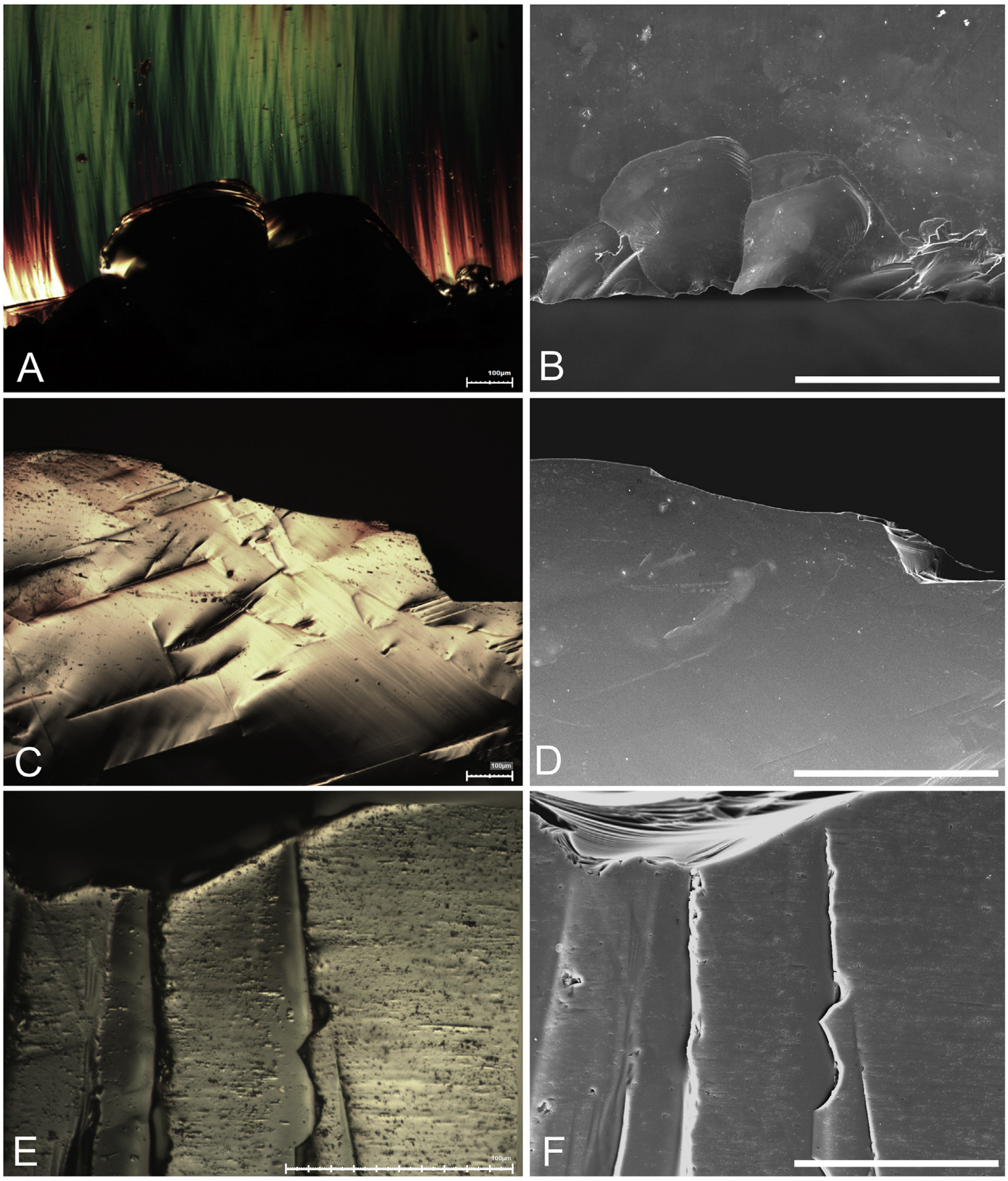

Fig. 1. Use-wear on rock crystal documented trough OLM (A, C, E) and SEM secondary electron detector (B, D, F). Scars outlines are more visible with SEM (B) than with OLM (A), especially because a higher depth of field, while striations are more visible with OLM (C, E) than with SEM (D, F). A) orig. mag.: 100×, scale bar: 100 µm; B) orig. mag.: 100×, scale bar: 500 µm; C) orig. mag.: 100×, scale bar: 100 µm; D) orig. mag.: 100×, scale bar: 500 µm; E) orig. mag.: 100×, scale bar: 500 µm; F) orig. mag.: 100×, scale bar: 500 µm. A and B correspond to bone cutting, and C to F to wood sawing actions.

selection of experimental cases, we broadly assess how they appear on the different raw materials, we determine which terminological issues must be taken into account, and how effective the aforementioned microscopes are to document them.

3.1. Edge fracturing (scarring, microchipping)

This is a very well described feature in the literature, also referred as scarring or microchipping. It refers to the micro scars produced on the tools' edges as a consequence of the applied force during use. Studies have traditionally considered the distribution along the edges, the morphology and the termination of the scars as dependent variables of the actions performed and worked materials. This, indeed, has been the base of the so-called low approach analysis, which is still being used in a way that maintains the guidelines stablished since the first proposals (Tringham et al., 1974; Odell et al., 1976; Hayden, 1979; Kamminga, 1982; Prost, 1990).

In all the studied materials different types of conchoidal fractures appear; these include scalar scars, step fractures, half-moon fractures and small crushing. These fractures appear on the edges of the tools, predominantly on their rims, but also on all the exposed quartz crystal ridges.

In general, the bigger the crystals, the better these scars can be documented and consequently used as diagnostic features. Regarding the materials studied here, these features are very clear for rock crystal (see Fig. 1a–b), just clear for vein quartz (Fig. 2), and really difficult to record on quartzite. As already noted (Kamminga,

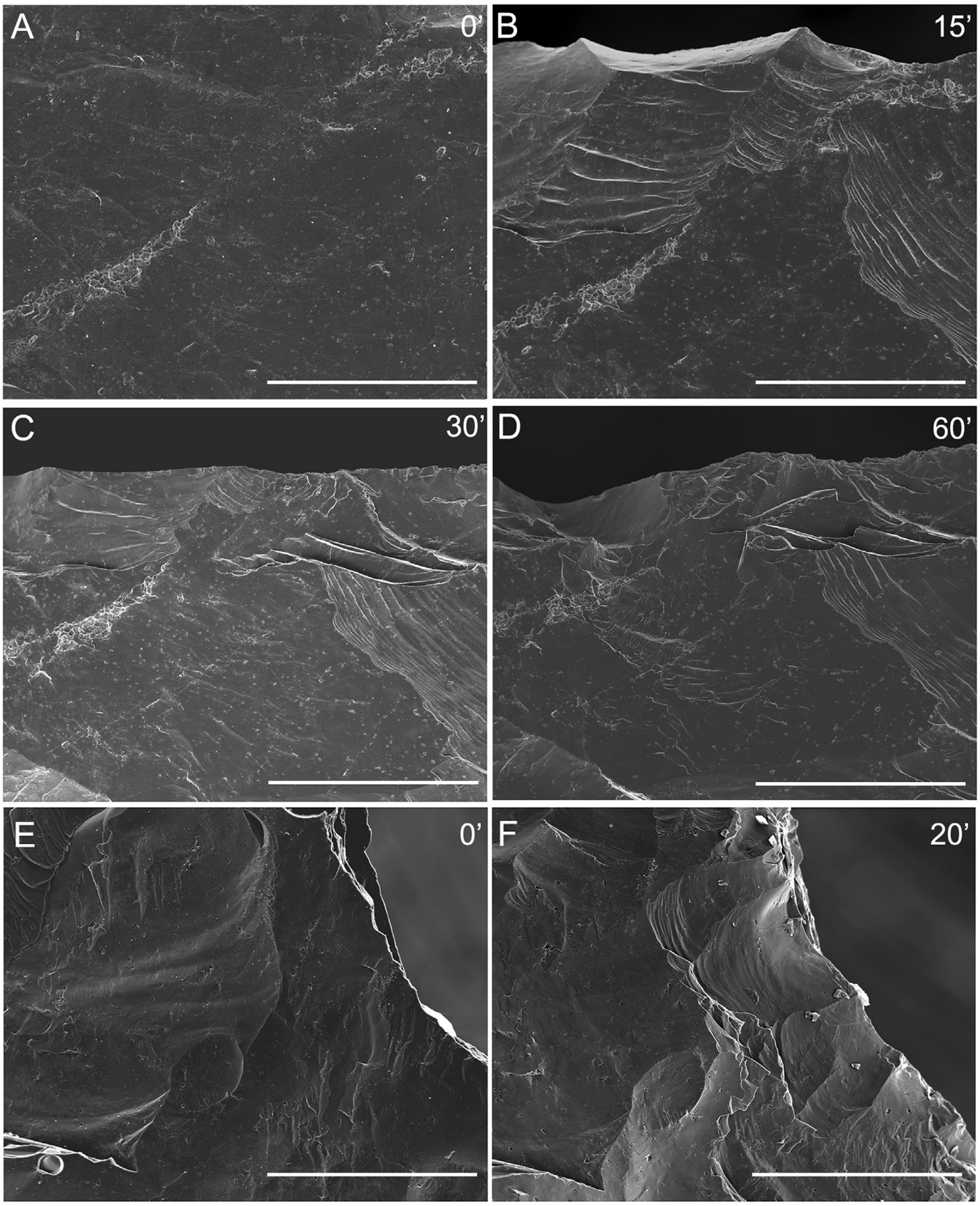

Fig. 2. Edge fracturing on quartz implements. Sequence of micrographs of the same portion of the edge before (A) and after 15, 30 and 60 min of wood scraping (B, C and D respectively); orig. mag.: 100×, scale bar: 500 μm; images of the same portion of the edge before (E) and after 20 min of bone scraping (F); orig. mag.: 100×, scale bar: 500 μm.

1982), problems appear when trying to distinguish individual scar patterns due to surface reflectivity, edge irregularities and unevenness in the quartz grains. These problems can be considerably overcome with the use of SEM; however, case materials such as quartzite continue to pose problems, as the scar limits are very hard to follow (Fig. 3).

There is no doubt that the identification of such scarring in experimental materials can effectively be achieved, especially when sequential series are available. The problem is the identification and the interpretation of these traces on archaeological materials. Probably, the main issue restricting the diagnostic value of this generic feature has to be with its equifinality. Indeed, many potential processes can lead to quite similar scarring patterns. These processes include anthropic actions as the edge modification by retouch, but also different postdepositional phenomenon quite common in archaeological contexts (as object transport, trampling, excavation and post-excavation damage…).

3.2. Linear features

We generically refer to as linear feature any naturally or anthropically induced mark on a stone surface susceptible to be microscopically identified. In spite of a certain trend to refer to these marks generically as striations, it must be said that many authors already focused their interest in establishing differences. For example, categories as “linear polishes” (Fischer et al., 1984) or

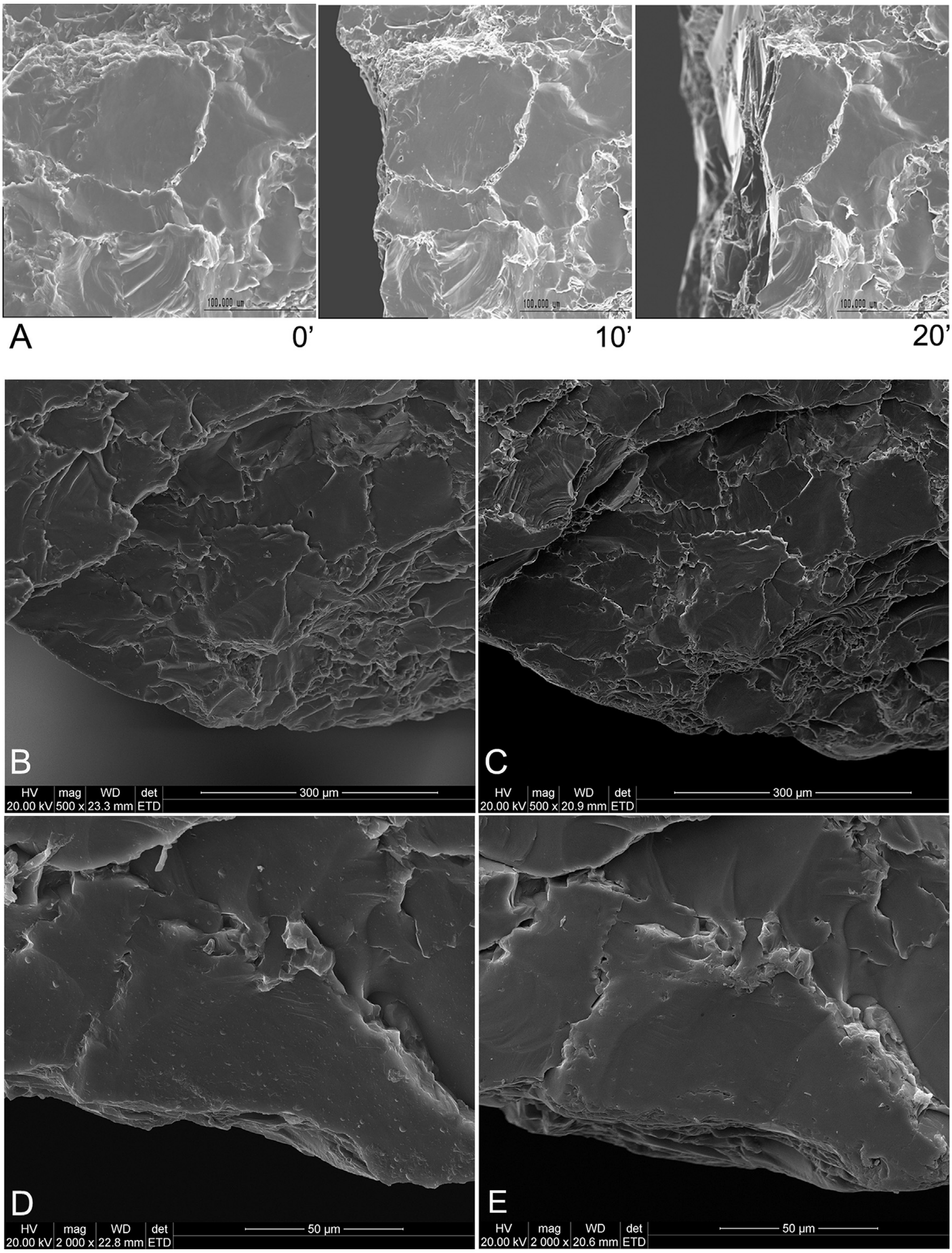

Fig. 3. Sequential experiments on quartzite. A) Edge scarring after 10 and 20 min of wood scraping; orig. mag. 250×, scale bar 100 μm; B and C microscarring on the edge before (B, cast of the fresh edge) and after 20 min of a butchery action; orig. mag. 500×, scale bar 300 μm; D and E details of B and C respectively; orig. mag.: 2000×, scale bar: 50 μm. Note on E some rounding and polish formation on the edge, as well as some linear friction features on the crystal.

"linear impact traces" (Moss, 1983), which usually appear associated to projectiles, or "bands of polish" and "lineal components of polish" (González Urquijo and Ibáñez Estévez, 1994), or even "linear trends" (Kamminga, 1982), which do not show clear limits and thus cannot be strictly considered striations, have been proposed.

Linear features are obviously important for microwear studies, as they are indicative of how a tool was orientated during use, of which type of motion was performed, and can even provide some clues on the type of worked material. The central role of these features was highlighted since the beginning of the discipline (e.g. Semenov, 1964; Keeley, 1980; Kamminga, 1982; Plisson, 1985; Mansur-Franchomme, 1986; Juel Jensen, 1994). Also, a kind of threefold dimension on them (functional, technological and post-depositional) has been noticed by most of authors.

The formation processes of the different linear friction features have been intensively debated. Globally, they are understood as marks produced by abrasive particles on the stone surfaces, these particles being variated in nature and origin. These particles can come from the worked material, from the damage of the tool during use, or they can be intentionally or unintentionally added to the interfacial medium. Obviously, linear features are not restricted to the active edges, as they often appear on other parts of the tools, due to the result of friction actions occurred during production, use and postdepositional processes.

Some basic variables such as length and width have been proposed to be measured to classify the linear features (e.g. Keeley, 1980; Mansur-Franchomme, 1983, 1986), but this quantitative approach has only been occasionally used to assist the usewear interpretation of archaeological tools. Actually, questions regarding their type, intensity and association degree with other wear features, are the preferred interpretative criteria.

Although different classifications and a variated terminology (which sometimes turns out to be quite confusing) have been proposed, linear features have mainly been divided into two big groups: sleeks (narrow and fine striations), and furrows (large and rough ones) (Table 2, and references therein). The former tend to have smooth and regular margins, and seem to respond to the plastic behaviour of the stone surface. The latter, on the contrary, tend to show irregular margins, "which are torn, or broken, or shattered as material was removed by excavation or microfracturing in a way that is somewhat analogous to ploughing" (Kamminga, 1982: 12), and must be explained by the brittle behaviour of the stone surfaces (Knutsson, 1988a).

As it has been noted before (e.g. Kamminga, 1982; Sussman, 1988; Knutsson, 1988a) on the materials studied here there is a clear predominance of the furrow-type. Thus, on quartz, rock crystal and quartzite it is easy to observe scratches in the form linear arrays of microscopic cracks, or holes formed from cracks, caused by brittle fracture after material fatigue in the subsurface zone (Fig. 4). These features have been also referred to as "chatter marks", "crescent", or "incipient cone cracks with shoulder breakage" in other contexts (e.g. Knutsson, 1988a; Madhavaraju et al., 2009). Differences between the studied materials do not seem to be linked to the chemical composition or to the toughness of these raw materials, so we likely have to take into account their differences in terms of crystal grain size. The larger the crystals are, the longer the linear marks tend to appear. Apart from simply the dimensions, it is very important that the homogeneity of the crystal topography (derived from the cleavage planes characteristic of each variety), which situates the rock crystal on one end and the quartzite at the other, placing the vein quartz in an intermediate position.

Sleek striations are really rare. Among the materials studied here, they have only been documented with a certain abundance on rock crystal, and usually associated to already modified surfaces (Fig. 5). Fig. 6 illustrates a continuous obliteration process sequentially recorded in a wood-cutting action, where in advanced stages of use narrow striations with very clear margins appear superimposed to furrow-like striations. These sleeks mostly consist of V-shaped grooves apparently created by an abrasive particle on an already plastically deformed surface, likely due to dislocation within the crystal structure, although in other

Table 2
Summary of the main terminological contributions on the description of the linear features regarding the two main groups considered here: sleeks and furrows.

References	Sleeks	Furrows
Semenov, 1964: 115	Striations: Tiny streaky scratches	Striations (generic use of terms such as scratches, furrows, lines, grooves, and wear striations)
Del Bene, 1979	Striae: formed by addition and translocation of materials	
Lawn and Marshall, 1979:72		Partial Hertzian Cracks
Keeley, 1980:23	Striations: subdivided according to width and depth	Abrasion tracks: often with parallel running, deep tracks
Kamminga, 1979:148 1982:12	Sleeks: linear features caused by plastic deformation	Scratches or furrows: tears in the surface due to microfracturing
Mansur, 1982	Smooth-bottomed through	Rough-bottomed through
Mansur-Franchomme, 1986:95	*Striae à fond lise, en forme de ruban*	*À fond rugueux*
Levi Sala, 1996: 12–13; 68	Linear features: generic term Sleeks: plastic deformation	Striations: furrows or grooves in the polished surface Grooves: opposed to linear features, form on the polished surface principally by microchips removed from the used edge during work
Knutsson et al., 1988	Striations- Linear features- Sleeks: narrow plastic deformations	Striations-Linear features: irregular striations
Sussman, 1988: 13–14	Striae: linear features with smooth-bottom	Linear grooves: gouges or rough bottom striations; Partial hertzian cones
Hurcombe, 1992:58	Sleeks	Crescent cracks: partial surface rings around the contact zone
Fullagar, 2006:222	Sleeks: smooth cross-section, likely plastic deformation of the surface	Furrows: ripping the surface and with jagged margins; continuous or discontinuous
Taipale, 2012: 36, 39	Sleeks: narrow plastic deformations	Discontinuous striations; Irregular striations; Hertzian cone cracks
Quartz exoscopy (Torcal and Tello, 1992; Madhavaraju et al. 2009, and refs. therein)		Striations, grooves, chatter marks

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005

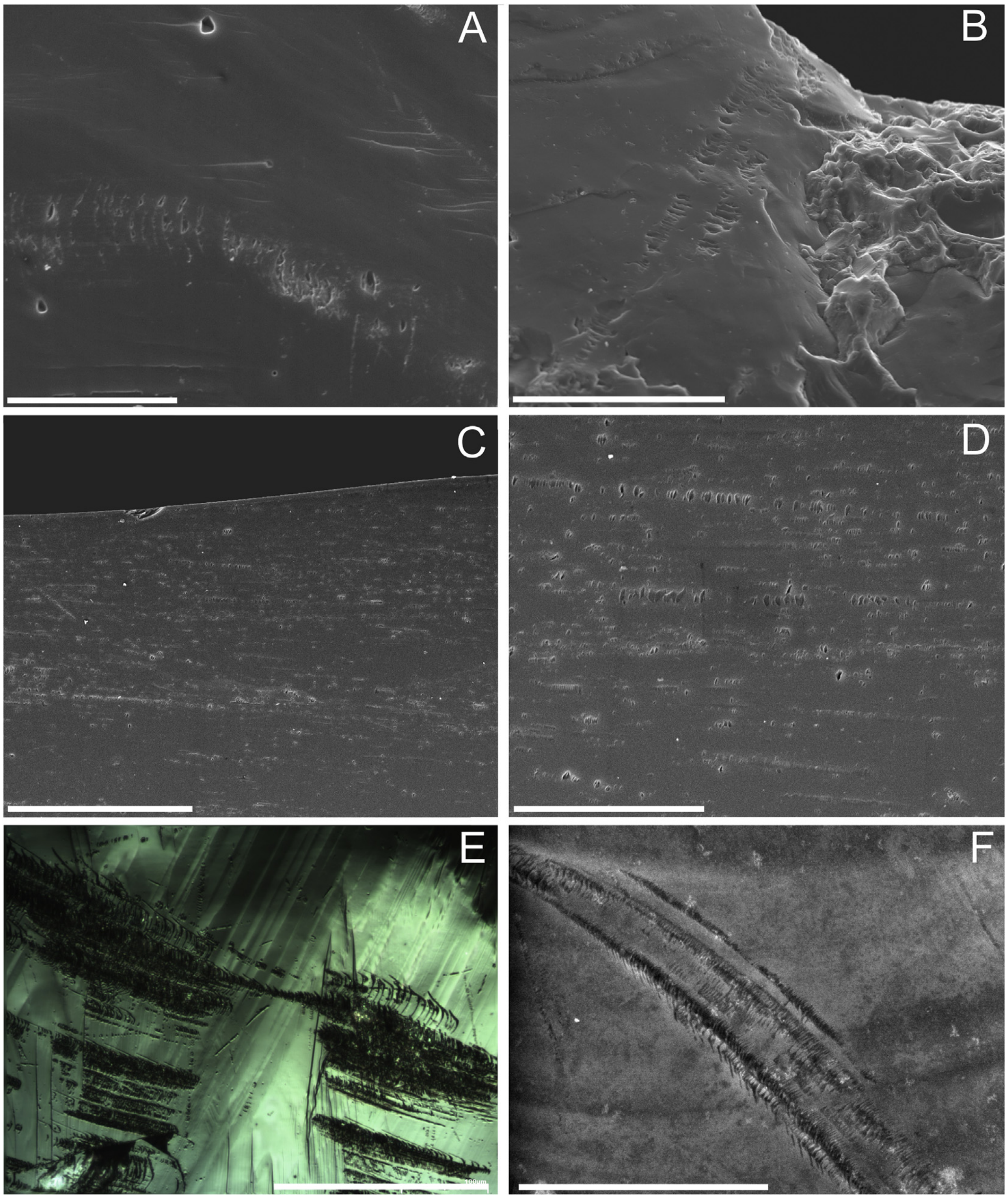

Fig. 4. Linear features exhibiting Hertzian cones on quartz (A), quartzite (B), and rock crystal (C, D, E and F). A) orig. mag.: 2000×, scale bar: 20 μm, cutting fresh bone; B) orig. mag.: 1000×, scale bar: 50 μm; butchering C) orig. mag.: 500×, scale bar: 100 μm, wood sawing; D) orig. mag.: 1500×, scale bar: 30 μm, wood sawing; E) orig. mag.: 500×, scale bar 100 μm, archaeological artefact; F) orig. mag.: 3000×, 50 μm, archaeological artefact.

cases what is preserved seems to be just the deeper part of a furrow-like striation.

Morphological differences among the linear friction features can be noted, but relationships between them and worked materials are hard to establish. There is a general trend to record clearer "chatter-mark" morphologies and more detachment of particles when working hard materials. This leads, for example, to propose the terms "wood striation" and "straight-sided striation" (Knutsson, 1988a; Knutsson et al., 2015) (Fig. 7). Although accepting the appropriateness of these observed associations, it is worth noting that in the tribo-systems several variables take part in the generation of these linear friction features: the physical characteristics of the elements (whether these are abrasive particles or an incident body), the characteristics of the interfacial medium (which affect the contact conditions), and the energy of the dynamic contact between surfaces (Knutsson, 1988a; Ollé and Vergès, 2008; Key et al., 2015). The different combinations of these variables (and other more specific like the holding properties of the worked material) would then promote the formation of more or less linear friction features and lead to the variability recorded in this group of traces.

3.3. *Polish*

Probably, this is the more described and debated wear feature in microwear analysis literature. It generally refers to the stone tool surface levelling due to the contact with another material. During use (but also during production or once the stone tool is

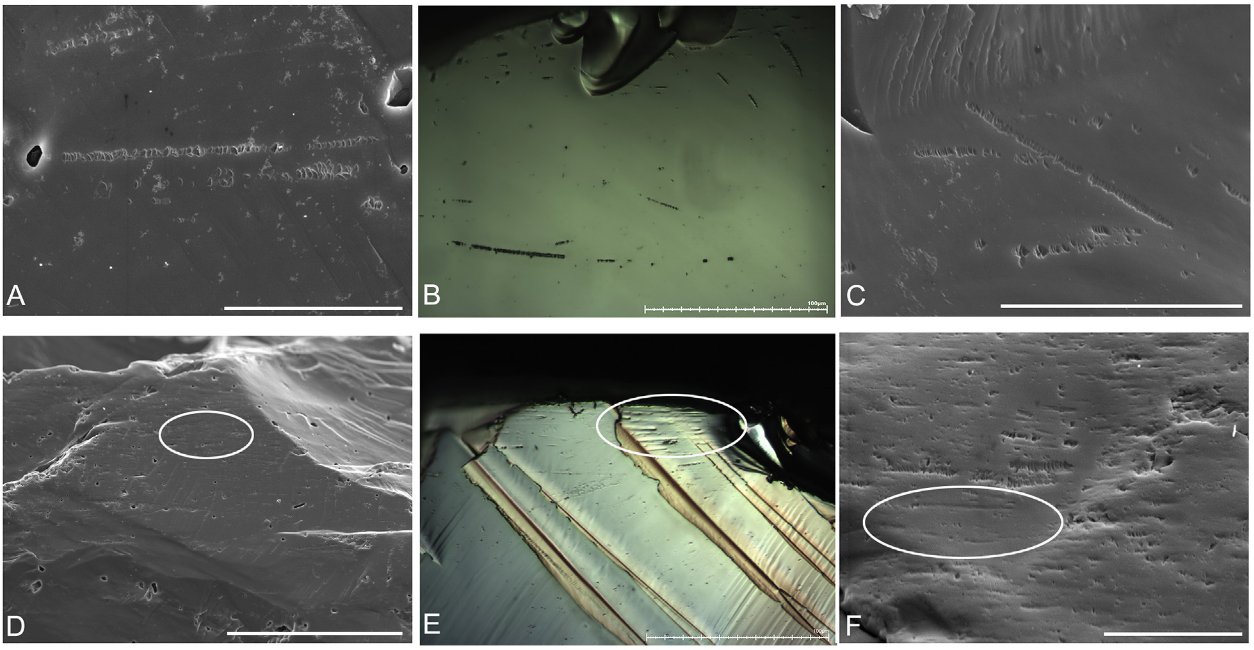

Fig. 5. Furrow striations on quartz (A), rock crystal (B) and quartzite (C). Combination of furrows and sleeks on quartz (D), rock crystal (E) and quartzite (F). White ellipses mark some of the sleeks. In all cases the action was wood cutting/sawing, except in E, which corresponds to a bone cutting action. A) orig. mag.: 2500×, scale bar: 20 μm; B) orig. mag.: 500 ×, scale bar: 100 μm; C) orig. mag.: 3500×, scale bar: 20 μm; D) orig. mag.: 500×, scale bar: 100 μm; E) orig. mag.: 500×, scale bar: 100 μm; F) orig. mag.: 2000× scale bar: 20 μm.

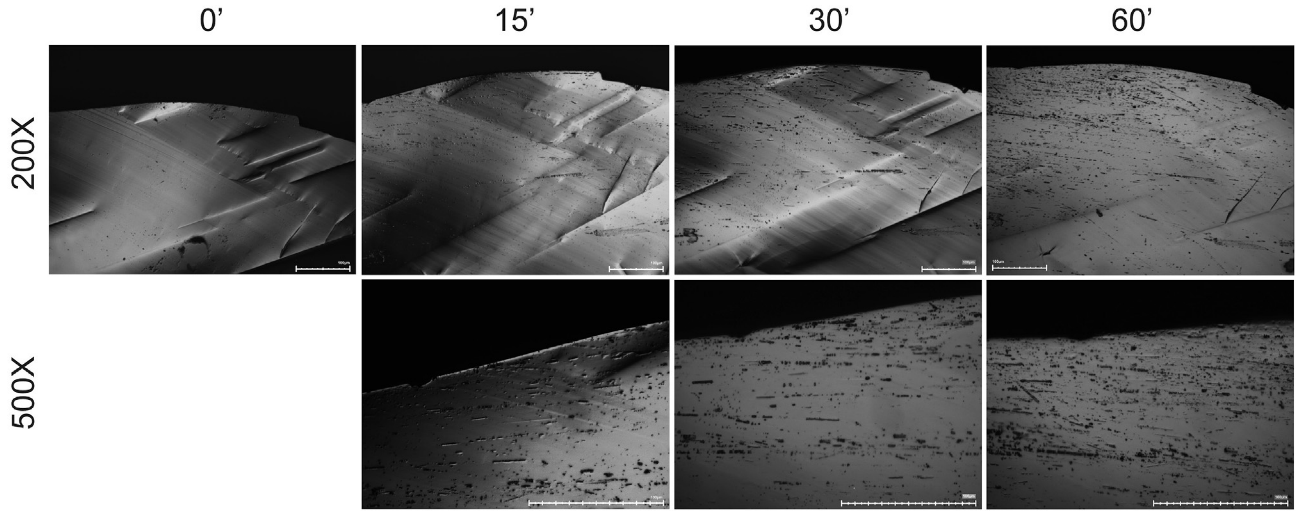

Fig. 6. Sequential experiment on rock crystal in a wood sawing activity, with intensive striation formation and a final smooth edge; orig. mag. 200×, scale bar: 100 μm.

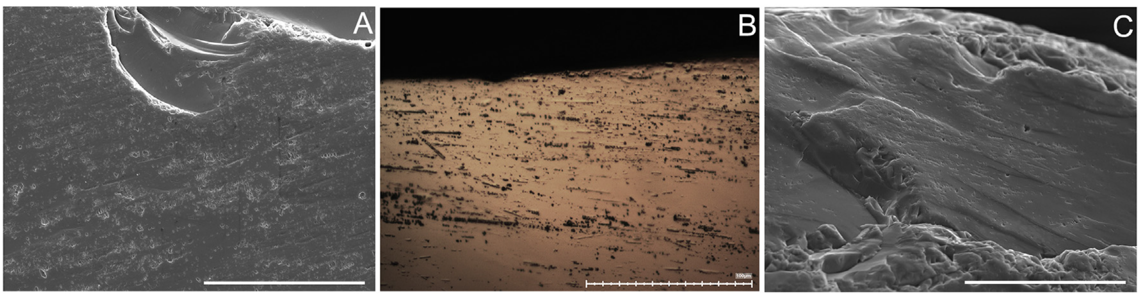

Fig. 7. Furrow striations after sawing wood. A), quartz, orig. mag.: 1000×, scale bar: 50 μm; B) rock crystal, orig. mag.: 500×, scale bar: 100 μm; C) quartzite, orig. mag.: 1000×, scale bar: 50 μm.

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005

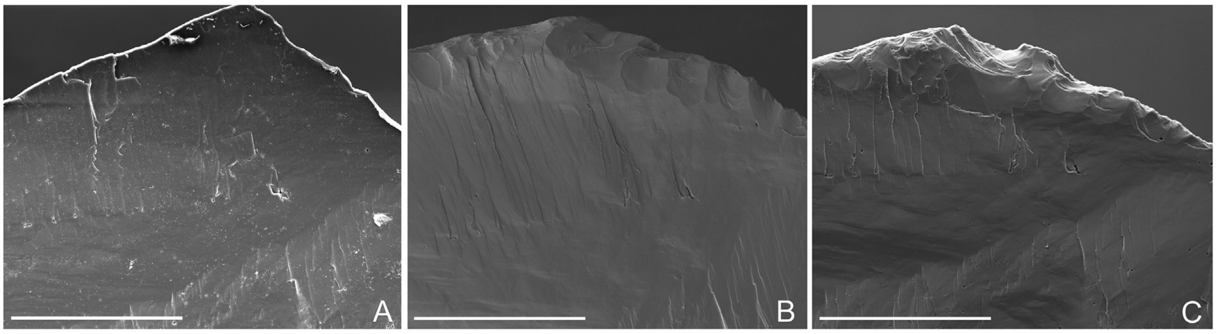

Fig. 8. A control point on a quartz edge after hide scraping: before use (A), after 30 min of use (B) and 60 min (C). Micrographs taken with a high vacuum SEM secondary electron detector, orig. mag.: 250×, scale bar 200 μm.

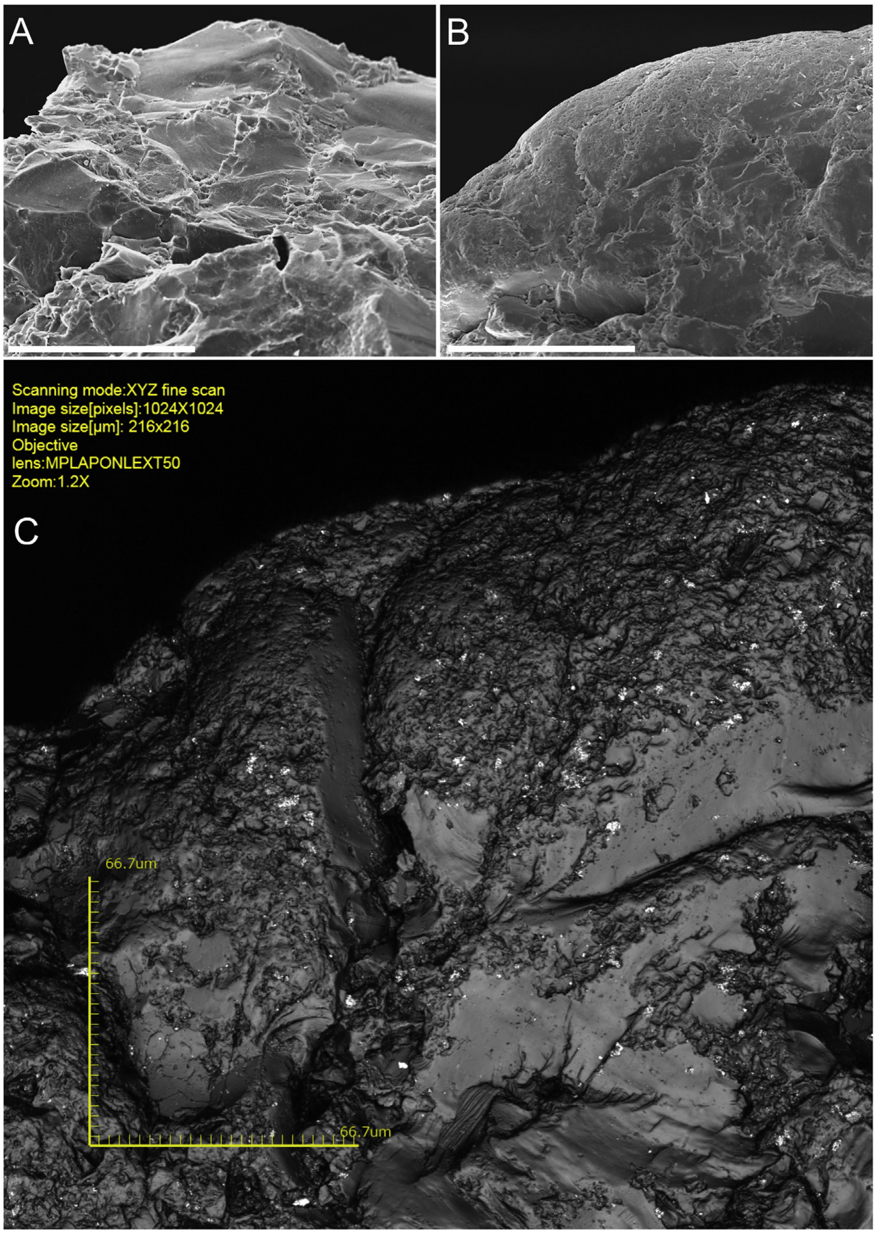

Fig. 9. Formation of abrasive wear on a quartzite artefact after hide scraping for 45 min; A) large crystals on the fresh edge; B) worn surface on the same spot showed in A; C) detail of the central area in B under the LSCM, with the abraded crystal and a clear smoothing of the surface. A, B) orig. mag.: 250×, scale bar: 200 μm; C) scale bar: 66.7 μm.

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005

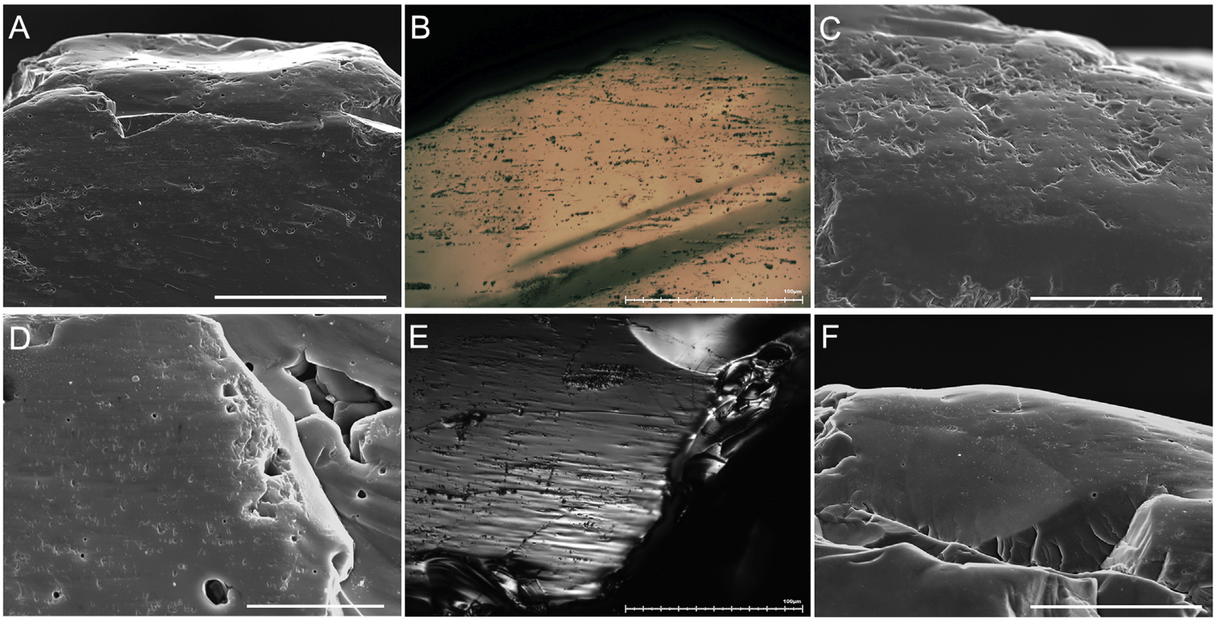

Fig. 10. Well-developed polish on quartz (A, D), rock crystal (B, E) and quartzite (C, D). A) orig. mag.: 250×, scale bar: 200 µm, cutting fresh bone; B) orig. mag.: 500×, scale bar: 100 µm, wood sawing; C) orig. mag.: 500×, scale bar: 100 µm, cane scraping; D) orig. mag.: 2000×, scale bar: 20 µm, cutting fresh bone; E) orig. mag.: 500×, scale bar: 100 µm, bone sawing; F) orig. mag.: 1000×, scale bar: 50 µm, bone sawing.

abandoned), the friction caused by that contact causes a removal of surface material (abrasion) on several scales, from broad roughening to smoothing into a glossy surface.

The polish formation processes have been widely discussed (e.g. Witthoft, 1967; Anderson, 1980a, 1980b; Masson et al., 1981; Meeks et al., 1982; Mansur-Franchomme, 1983; Unger-Hamilton, 1984; Vaughan, 1985; Plisson and Mauger, 1988; Fullagar, 1991; Hurcombe, 1992; Yamada, 1993; Levi Sala, 1996; Christensen, 1998; Lerner et al., 2007). In previous works we contributed to this debate mainly basing on SEM analysis and sequential experiments (Ollé and Vergès, 2008; Aranda et al., 2014; Ollé and Vergès, 2014; Pedergnana and Ollé, 2014), and borrowing theoretical concepts from materials sciences and tribology (e.g. OECD, 1969; Bhushan and Gupta, 1991; Hutchings, 1992; Williams, 2005; Kato, 2006; Momber, 2015), as this approach had been previously demonstrated especially useful (Knutsson, 1988a; Fullagar, 1991; Levi Sala, 1996; Donahue and Burroni, 2004; Anderson et al., 2006; Adams et al., 2009; Delgado-Raack et al., 2009).

Our results led us to consider the polish formation as a clear attritional process, in which a combination of brittle and plastic deformations occur in a very dynamic way, and that leads to worn surfaces by smoothing of the asperities on the stone microrelief. No layer formation has been observed. As other authors already noted (in a very special way after the works by Knutsson and colleagues continuously referred in this article), quartz and similar materials have a more brittle behaviour compared to cryptocrystalline materials such as chert (where plastic deformation is more evident).

Bearing this in mind, we propose to interpret features as edge rounding, smoothing by attrition and smoothing by plastic deformation as different steps of a single general process. Our sequential experiments including quartz, rock crystal and quartzite showed that a quite similar process can be observed, which starts with a strong edge microfracture and is followed by a progressive rounding of the crystal edges by micro-abrasion, and a more or less developed plastic deformation (compression) restricted to the more exposed points of the topography (and only if no subsequent fracturing occurs) (Fig. 8). Obviously, the particular representation, development, and distribution of the different wear features will vary depending on the performed actions, worked materials and use conditions.

Recently, the particularities of polish appearance and distribution for this group of rocks with respect to chert have been properly stressed (Clemente and Gibaja, 2009; Lemorini et al., 2014; Clemente-Conte et al., 2015; Márquez et al., 2016). However, the description of wear phenomena seems to require more accuracy. For instance, what seems to be a mechanical process has been sometimes referred to as corrosion, without having proved the existence of a "wear process in which chemical or electrochemical reaction" occurred (OECD, 1969). Another issue would be the reference to the different appearance of polish on the surfaces of crystals and on the "matrix". Combining different microscopes, we have documented that what can be interpreted as the "cement matrix" is, in fact, the abraded crystal. This is particularly clear in the case of quartzite; as discussed elsewhere (Pedergnana et al., 2016), the term matrix has no sense in the case of metaquartzites. At any rate, and, sequential experiments as the one in Fig. 9 show how a single crystal is abraded by use (hideworking in this case), which may resemble the smaller fraction of sedimentary rocks known as matrix when scanned with OLM. By taking advantage of the resolution of LSCM, a clear polish is observable on the more exposed points of the former microfractured crystal, which appear clearly smooth. This phenomenon can be explained, in our opinion, by a combination of brittle and plastic response of the rock surface to the stress caused by use.

Regarding the diagnostic value of the appearance of the polished surfaces with respect to the worked materials, so far, just a few general observations can be made for the raw materials studied here. In all cases, for instance, hard and/or silica-rich materials tend to produce flatter (more levelled) topographies, as while softer ones tend to show a rough surface, usually ploughed by a variable amount of furrows, and with really scarce plastic deformation. On the former, other than the levelling, other topographical traits (roughness, waviness) observed on well-developed polishes seem to be quite diagnostic. These are the cases of the really smooth and

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005

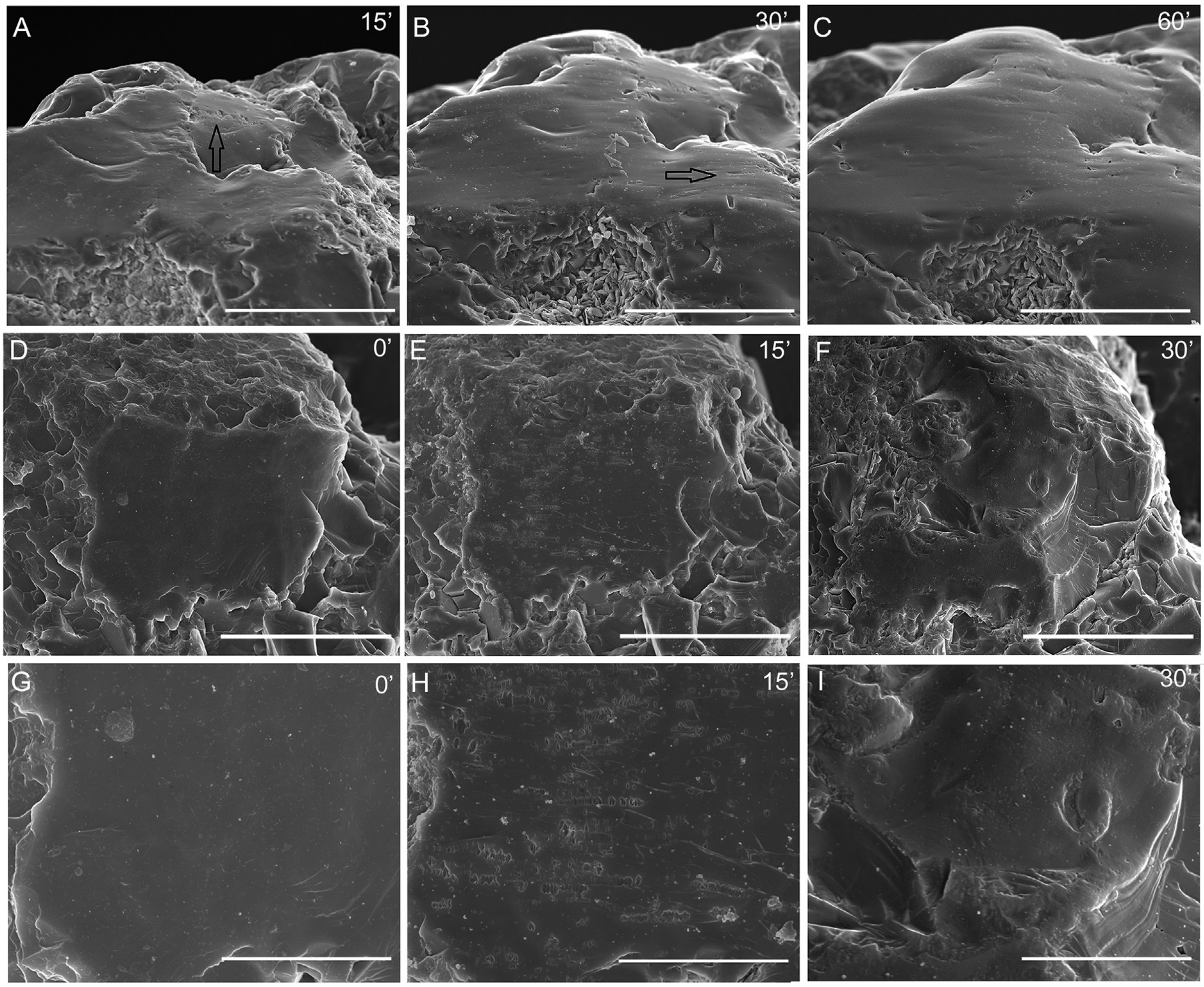

Fig. 11. Sequential experiments on quartzite showing wear development. A to C show the polish development after 15, 30, and 60 min of bone sawing respectively. Sleek striations may form on the polish and then disappear after the flattening of the surface during the process of polishing. Note the clear wavy aspect in the last stage. D to F show the wear formation on a flat surface of a quartz crystal after wood sawing before use (D, cast) and after 15 and 30 min. G to I are details of the same points. Note how after 15 min of use a number of furrows plough the crystals' surface, and how after 30 min these features absolutely disappear because of the detachment of part of the crystal. This, in turn, shows clear wear features in the form of edge microscarring and some smoothing. Micrographs taken with a high vacuum SEM secondary electron detector, A–F) orig. mag.: 1000×, scale bar: 50 µm; G–I) 2500×, scale bar 20 µm.

doomed surfaces for plant materials, of the wavy ones associated to fresh bone (Figs. 10 and 11).

4. Discussion

In summary, if we put aside the differences between raw materials, our research mainly supports the essentially attritional character of the wear process. As such, all the wear features referred to can be framed into this conception as, in all recorded observations, we have identified a high or small loss of matter as a result of the smoothing of the asperities of the microrelief and the loss of an edge portion by fracture and polish. Furthermore, the experiments clearly show the very dynamic behaviour of the tool's contact surfaces: use-wear traces are continuously generated and destroyed, so what we record through microscopic observation is the state at a specific moment during the process, not the final phase of an accumulative phenomenon (Fig. 11). We have also noticed differences between certain episodes in which brittle fracture or plastic deformation alternatively dominates during the use, as well as how edge microflaking often removes pre-existing plastically deformed areas (Ollé and Vergès, 2008). Therefore, "although many factors influence the final appearance of wear features, we do not distinguish between different processes, but rather between different phases of a single process, and therein lies the interest of the sequential monitoring method we propose" (Ollé and Vergès, 2014:69). The experiment shown in Fig. 6 illustrates how the edge of a rock crystal progressively wears during a three-step sawing action on green wood. This process begins with some long furrows produced after the edge microscarring, continues with the progressive scarring, more striations and slight edge rounding, and after 60 min of use shows obliterated furrows, a polished surface with clear signs of plastic deformation, partially covered by sleeks. A similar process can be observed in Fig. 12 on a quartzite tool used a similar action. Here a stronger edge scarring is initially appreciated, being the detached portions of it the responsible of the same type of furrows as in the previous example, and finishing after 30 min of work with a really smooth and doomed surface case, where the furrows practically disappeared.

So far, our results and observations are insufficient to properly assess the wear features on the materials studied here, especially taking into account the huge petrological variability in raw materials as vein quartz or quartzite. At any rate, what is clear is that

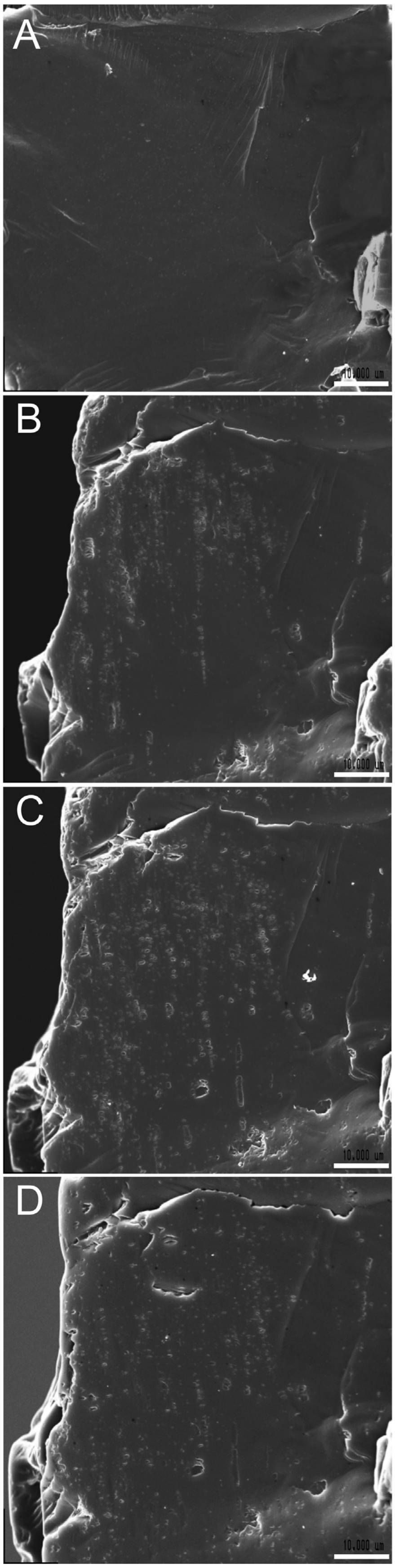

Fig. 12. Sequential experiment on quartzite showing wear development during a sawing action on green wood. Images of the fresh edge (A, cast), and after 10, 20 and 30 min of use. Note the initial loss of a portion of the edge, the progressive formation of parallel striations, and their obliteration at the third use-stage, in which a domed polish can be seen. Micrographs taken with a high vacuum SEM secondary electron detector, orig. mag.: 1000×, scale bar: 10 μm.

these rocks share an essentially brittle behaviour, quite different from other cryptocrystalline quartz varieties as chert of flint. It is for this reason that it made sense consider them together for this study.

Nevertheless, some differences between the wear features have been documented, and they likely derive from the specific material structure. This, and not the rock's chemical composition or hardness, determines its toughness and the way in which the edges wear. Variables like grain size, surface homogeneity, continuity, microtopography and smoothness seem to be determinant on the appearance and development of the wear features.

In this sense, for example brightness, which is one of the main criteria when describing microwear, seems to be strongly dependant on crystal size and arrangement. In rocks like chert, the more worn the surface, the brighter it is because the attritional process smooths it. But in rock crystal the original surface is extremely smooth (and so it naturally shines), and what wear always does is turning the surface rougher and duller. Neither on vein quartz nor on quartzite brightness can be used to properly identify polished areas (Figs. 10 and 13).

The ongoing experimental programmes consider a “checklist approach” to make easier in the future the comparisons on the wear features occurring on quartzose raw materials. Such an approach is commonly used in Earth sciences when dealing with microtextures of quartz grains (Torcal and Tello, 1992; Madhavaraju et al., 2009), and was effectively applied to usewear analysis by Knutsson (1988b: 65). Future steps on this field would require more specific results on each of the raw materials studied here, incorporating available systems of classification of the wear features (e.g. Adams et al., 2009) and already observed specific phenomena (e.g. Clemente-Conte and Gibaja, 2009; Márquez et al. in press).

Although postdepositional processes have not been considered in this article, it is worth noting that most of them imply mechanical phenomenon highly coincident with the stone tool use, and so, their effects on the stone surfaces tend to present morphological coincidences. So, a proper distinction of use-wear and postdepositional wear on archaeological artefacts would require a specific consideration of the distribution of the traces and, sometimes, a high magnification to properly identify features as the v-shaped impact pits (Fig. 14).

In terms of microscopes, we strongly support the complementary character of different techniques (e.g. Borel et al., 2014; Knutsson et al., 2015; Marreiros et al., 2015) (Fig. 13). The reflected light microscope is appropriate for analysing the varieties with large crystals, as rock crystal and vein quartz, but they revealed more limited when dealing with quartzite (Grace, 1990). Of course, results improve clearly when using differential interference contrast (DIC) and extended focus applications. SEM, on his part, adds a higher depth of field, the possibility of a higher magnification, and a general better quality view of the textural features thanks to the removal of the glare derived from the rock's optical properties. These advantages are very useful to describe features as the striations. Finally, we occasionally used the LSCM, and it proved to be highly efficient to image the details on crystal modification at high magnification. Its potential in terms of wear quantification has been proved for flint (Evans and Donahue, 2008),

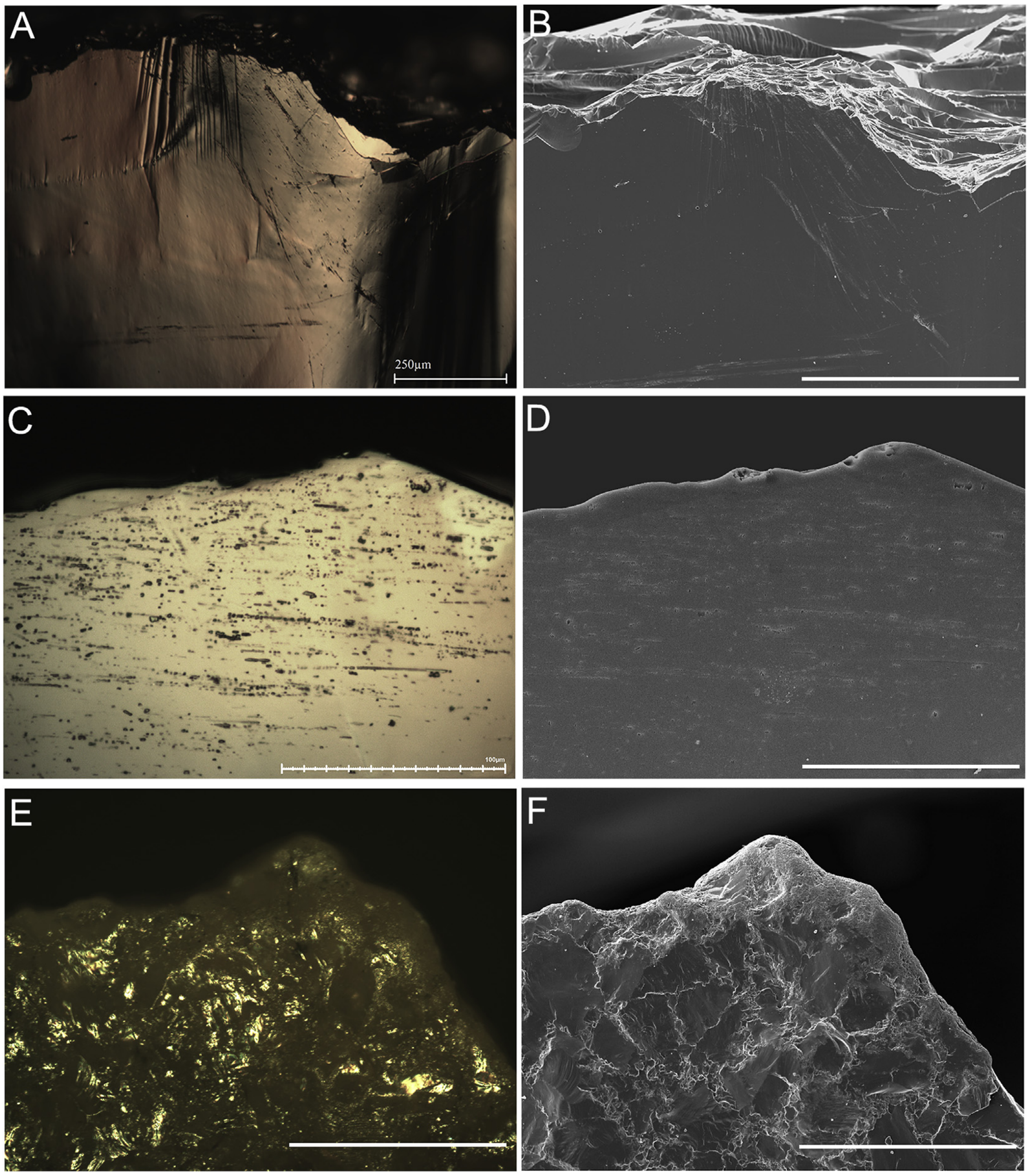

Fig. 13. Comparison of use-wear features on quartzose materials. The same points the lithic edges are imaged by means of two complementary microscopic techniques, OLM (A, C, E) and SEM secondary electron detector (B, D, F). A–B) Quartz, orig. mag. 100×; scale bars: 250 and 500 µm respectively, archaeological traces; C–D) rock crystal, orig. mag.: 500×, scale bar: 100 µm, wood sawing; E–F) quartzite, orig. mag.: 100×, scale bar: 500 µm hide scraping.

and only few data is available for the rocks we are dealing with (Stemp et al., 2013).

5. Final remarks

The results presented here aimed to contribute new data and observations to the up to date still scarce of reliable published works to be used as referential wear patterns on quartz-like materials.

After appropriate methodological procedures, use-wear analysis can effectively tackle functional as well as technical issues from quartz materials. In fact, we think that methodology should be adapted to each type of rock, possibly varying the combinations of microscopic techniques, magnifications, cleaning processes, etc. In fact, we noticed that for some lithologies optical light microscopy was enough to observe use-wear, but for others it was far to provide satisfactory results. And sequential experiments allowed making progress in the comprehension of the wear formation processes on a group of materials mineralogically similar (macrocrystaline quartz), but quite different in structure.

The use of a very wide range of magnifications is extremely efficient, as use-wear is made up of a variety of features (micro-flaking, edge rounding, striations, polishes, etc.), each of which has specific requirements in terms of magnification and image resolution in order to be properly documented. So, different magnifications can give rise to very accurate descriptions of the diagnostic traits of wear features.

The trials with the LSCM proved to be really encouraging, not only by the clear potential of the technique in terms of quantification, but also in terms of imaging. The above mentioned “flatting” effect of the SEM is eliminated, keeping a very good image resolution up to c. 2000×, which allows, for example, properly interpret

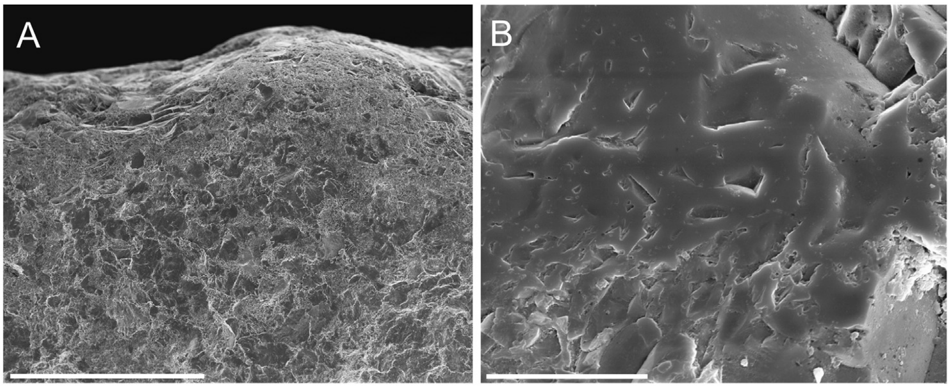

Fig. 14. Example of a naturally abraded edge on a quartzite fragment. At low magnification (A) a wear pattern (edge rounding and rough surface) very similar to some use experiments (e.g. hide working) can be observed. But at a higher magnification some diagnostic features as v-shaped impact pits can be documented, which allows us to identify this piece as naturally abraded instead of a used one. A) orig. mag.: 50×, scale bar: 1 mm; B) orig. mag.: 2000×, scale bar: 20 µm.

as a progressive abrasion of a large crystal what under the optical microscope would seem to be just an area of smaller crystals.

The essentially brittle behaviour of quartz restricts both the appearance and the preservation of wear features (striations, plastic deformations …). For that reason, isolated wear features, which in other materials perhaps would not be considered when analysing archaeological materials, must in this case be taken into account.

The diagnostic character of the described features depends on what we are searching for: the identification of the used edges (high), the tool's kinematics (medium), and the worked material (medium to low).

Acknowledgments

We would first thank the organisers of the B5 session of the 2014 UISPP conference New approaches to the study of quartz lithic industries, Carlos Rodríguez Rellán and Arturo de Lombera Hermida, for inviting us to present a contribution (and for their patience waiting for it). We are also grateful to the Servei de Recursos Científics i Tècnics staff of the Rovira i Virgili University (Tarragona, Spain) for their help during SEM sessions. This work was developed within the frame of the Spanish project CGL2012-38434-C03-03 (Ministerio de Economía y Competitividad), the Catalan project SGR 2014-899 (AGAUR, Generalitat de Catalunya) and the French-Spanish project of cooperation (Mérimée). LSCM analysis was performed in collaboration with A. Evans, in the framework of the AH/L0068X/1 project (Arts and Humanities Research Council, UK). A.P. is the beneficiary of a FI-DGR predoctoral grant from the Generalitat de Catalunya (2014FI_B 00539). J.L. F-M is the beneficiary of a FPI predoctoral grant from the Spanish MINECO (BES-2015-074931). S.M. is the beneficiary of the National United Kingdom AHRC Ph.D Schorlarship and the College of Humanities Grant from the University of Exeter (1359154). We would also like to thank Matt Swieton and Amy Elmasri Thompson for their English revision of the manuscript. Finally, we are deeply grateful to K. Knutsson, who declining to maintain the reviewer's anonymity kindly provided thoughtful and constructive comments to the manuscript (unfulfillments and remaining errors, however, are entirely attributable to the authors).

References

Adams, J.L., Delgado-Raack, S., Dubreuil, L., Hamon, C., Plisson, H., Risch, R., 2009. Functional analysis of macro-lithic artefacts: a focus on working surfaces. In: Sternke, F., Eigeland, L., Costa, L.-J. (Eds.), Non-flint Raw Material Use in Prehistory. Old Prejudices and New Directions. UISPP - Proceedings of the World Congress (Lisbon, 4-9 September 2006), B.A.R. International Series, vol. 1939. Archaeopress, Oxford, pp. 43–66.

Anderson, P.C., 1980a. A scanning electron microscope study of microwear polish and diagnostic deposits on used stone tool working edges. Lithic Technology 9, 32–33.

Anderson, P.C., 1980b. A testimony of prehistoric tasks: diagnostic residues on stone tool working edges. World Archaeology 12, 181–194.

Anderson, P.C., Georges, J.-M., Vargilou, R., Zahouani, H., 2006. Insights from a tribological analysis of the tribulum. Journal of Archaeological Science 33, 1559–1568.

Aranda, V., Canals, A., Ollé, A., 2014. Experimental program for the detection of use wear in quartzite. In: Bicho, N.F., Gibaja, J.F., Marreiros, J. (Eds.), Proceedings of the International Conference on Use-wear Analysis. Use-wear 2012. Cambridge Scholars Publishing, Newcastle upon Tyne, pp. 45–54.

Bhushan, B., Gupta, B.K., 1991. Handbook of Tribology. Materials, Coatings, and Surface Treatments. McGraw - Hill, Inc., New York.

Borel, A., Ollé, A., Vergès, J.M., Sala, R., 2014. Scanning Electron and Optical Light Microscopy: two complementary approaches for the understanding and interpretation of usewear and residues on stone tools. Journal of Archaeological Science 48, 46–59.

Carbonell, E., Canals, A., Sauceda, I., Barrero, N., Carbajo, Á., Díaz, Ó., Díaz, I., García, M., García, M., Gil, J., Guerra, S., León, L.M., Mancha, S., Mancha, E., Mejías, D., Merino, R.M., Morano, M., Morcillo, A., Muñoz, L., Rodríguez, A., Julià, R., Giralt, S., Falguères, C., 2005. La grotte de Santa Ana (Cáceres, Espagne) et l'évolution technologique au Pléistocène dans la Péninsule ibérique. L'Anthropologie 109, 267–285.

Clemente-Conte, I., 1995/2008. Instrumentos de trabajo líticos de los yámanas (canoeros-nómadas de la Tierra del Fuego): una perspectiva desde el análisis funcional. Ph.D. thesis, Dept. d'Antropologia Social i de Prehistòria. Universitat Autònoma de Barcelona. Url: http://www.tdx.cat/TDX-0415108-171300.

Clemente-Conte, I., Lazuén Fernández, T., Astruc, L., Rodríguez Rodríguez, A.C., 2015. Use-wear analysis on nonflint lithic raw materials: the cases of quartz/quartzite and obsidian. In: Marreiros, J.M., Gibaja Bao, J.F., Ferreira Bicho, N. (Eds.), Use-wear and Residue Analysis in Archaeology. Springer, pp. 59–81.

Clemente, I., Gibaja, J.F., 2009. Formation of use-wear traces in non-flint rocks: the case of quartzite and rhyolite. Differences and similiraties. In: Sternke, F., Eigeland, L., Costa, L.-J. (Eds.), Non-flint Raw Material Use in Prehistory. Old Prejudices and New Directions. UISPP - Proceedings of the World Congress (Lisbon, 4-9 September 2006), B.A.R. International Series, vol. 1939. Archaeopress, Oxford, pp. 93–98.

Clemente, I., Igreja, M.d.A., 2009. Recent functional studies on non flint stone tools: methodological improvements and archaeological inferences. In: Proceedings of the Workshop 23-25 May 2008, Lisboa - Proceedings of the Workshop [CD-ROM], Lisboa.

Christensen, M., 1998. Processus de formation et caractérisation physico-chimique des polis d'utilisation des outils en silex. Application à la technologie préhistorique de l'ivoire. Bulletin de la Société Préhistorique Française 95, 183–201.

Del Bene, T.A., 1979. Once upon a striation: current models of striation and Polish formation. In: Hayden, B. (Ed.), Lithic Use-wear Analysis. Academic Press, New York, pp. 167–177.

Delgado-Raack, S., Gómez-Gras, D., Risch, R., 2009. The mechanical properties of macrolithic artifacts: a methodological background for functional analysis. Journal of Archaeological Science 36, 1823–1831.

Derndarsky, M., 2009. Use-wear analysis of the Middle Palaeolithic quartz artefacts from the Tunnelhöhle, Styria. In: Clemente, I., Igreja, M.d.A. (Eds.), Recent Functional Studies on Non Flint Stone Tools: Methodological Improvements and Archaeological Inferences, Proceedings of the Workshop 23-25 May 2008, Lisboa - Proceedings of the Workshop [CD-ROM], Lisboa.

Derndarsky, M., Ocklind, G., 2001. Some preliminary observations on subsurface damage on experimental and archaeological quartz tools using CLSM and dye. Journal of Archaeological Science 28, 1149–1158.
Donahue, R.E., Burroni, D., 2004. Lithic microwear analysis and the formation of archaeological assemblages. In: Walker, E.A., Wenban-Smith, F., Healy, F. (Eds.), Lithics in Action. Oxbow Books, Oxford, pp. 140–148.
Eigeland, L., 2009. The cold case. Non flint raw materials studies in Norway. In: Clemente, I., Igreja, M.d.A. (Eds.), Recent Functional Studies on Non Flint Stone Tools: Methodological Improvements and Archaeological Inferences, Proceedings of the Workshop 23-25 May 2008, Lisboa - Proceedings of the Workshop [CD-ROM], Lisboa.
Evans, A.A., Donahue, R.E., 2008. Laser scanning confocal microscopy: a potential technique for the study of lithic microwear. Journal of Archaeological Science 35, 2223–2230.
Fernández-Marchena, J.L., 2013. Análisis funcional de los artefactos en cristal de roca de Cova Eirós. Aproximación experimental, análisis traceológico y de residuos. Master thesis, Universitat Rovira i Virgili, Tarragona.
Fernández-Marchena, J.L., Ollé, A., 2016. Microscopic analysis of technical and functional traces as a method for the use-wear analysis of rock crystal tools. Quaternary International (in press). http://dx.doi.org/10.1016/j.quaint.2015.10.064.
Fischer, A., Hansen, P.V., Rasmussen, P., 1984. Macro and micro wear traces on lithic projectile points. Experimental results and prehistoric examples. Journal of Danish Archaeology 3, 19–46.
Fullagar, R.L.K., 1991. The role of silica in polish formation. Journal of Archaeological Science 18, 1–25.
Fullagar, R., 2006. Residues and usewear. In: Balme, J., Paterson, A. (Eds.), Archaeology in Practice. A Student Guide to Archaeological Analyses. Blackwell Publishing Ltd., Malden, pp. 207–234.
González Urquijo, J.E., Ibáñez Estévez, J.J., 1994. Metodología de Análisis funcional de instrumentos tallados en sílex. Universidad de Deusto, Bilbao.
Grace, R., 1990. The limitations and applications of use wear analysis. In: Gräslund, B., Knutsson, H., Knutsson, K., Taffinder, J. (Eds.), The Interpretative Possibilities of Microwear Studies. Societas Archaelogica Upsaliensis, Uppsala, pp. 9–14.
Grace, R., 1996. Use-wear analysis. The state of the art. Archaeometry 38, 209–229.
Greiser, S.T., Sheets, P.D., 1979. Raw material as a functional variable in use-wear studies. In: Hayden, B. (Ed.), Lithic Use-wear Analysis. Academic Press, New York, pp. 289–396.
Hayden, B., 1979. Lithic Use-wear Analysis, Studies in Archaeology. Academic Press, New York, p. 205.
Hurcombe, L.M., 1992. Use-wear Analysis and Obsidian: Theory, Experiments and Results. J.R. Collis, Sheffield.
Hutchings, I.M., 1992. Tribology. Friction and Wear of Engineering Materials. CRC Press, Boca Raton, Florida.
Ibáñez, J.J., González-Urquijo, J.E., Gibaja, J., 2014. Discriminating wild vs domestic cereal harvesting micropolish through laser confocal microscopy. Journal of Archaeological Science 48, 96–103.
Igreja, M.d.A., 2009. Use-wear analysis of non-flint stone tools using DIC microscopy and resin casts: a simple and effective technique. In: Clemente, I., Igreja, M.d.A. (Eds.), Recent Functional Studies on Non Flint Stone Tools: Methodological Improvements and Archaeological Inferences, Proceedings of the Workshop 23-25 May 2008, Lisboa - Proceedings of the Workshop [CD-ROM], Lisboa.
Juel Jensen, H., 1994. Flint Tools and Plant Working. Hidden Traces of Stone Technology. Arus University Press.
Kamminga, J., 1979. The nature of use-polish and abrasive smoothing on stone tools. In: Hayden, B. (Ed.), Lithic Use-wear Analysis. Academic Press, New York, pp. 143–157.
Kamminga, J., 1982. Over the Edge. Functional Analysis of Australian Stone Tools. Anthropology Museum, University of Queensland, St. Lucia, Queensland.
Kato, K., 2006. Classification of wear mechanisms/models. In: Stachowiak, G.W. (Ed.), Wear. Materials, 20 Mechanisms and Practice. Wiley, West Sussex, England, pp. 9–20.
Keeley, L.H., 1980. Experimental Determination of Stone Tools Uses: a Microwear Analysis. The University of Chicago Press, Chicago.
Key, A.J.M., Stemp, W.J., Morozov, M., Proffitt, T., De la Torre, I., 2015. Is loading a significantly influential factor in the development of lithic microwear? An experimental test using LSCM on Basalt from Olduvai Gorge. Journal of Archaeological Method and Theory 22, 1193–1214.
Knutsson, K., 1988a. Patterns of Tools Use. Scanning Electron Microscopy of Experimental Quartz Tools. Societas Archaeologica Upsalensis (AUN 10), Uppsala.
Knutsson, K., 1988b. Making and Using Stone Tools. The Analysis of the Middle Neolithic Sites with Flint in Västerbotten, Northern Sweden. Societas Archaelogica Upsaliensis, (AUN11), Uppsala.
Knutsson, K., Dahlquist, B., Knutsson, H., 1988. Patterns of tool use. The microwear analysis of the quartz and flint assemblage from the Bjurselet site, Vosterbotten, Northern Sweden. In: Beyries, S. (Ed.), Industries lithiques. Tracéologie et Technologie. John and Erika Hedges Ltd., Oxford, pp. 253–294.
Knutsson, H., Knutsson, K., Taipale, N., Tallavaara, M., Darmark, K., 2015. How shattered flakes were used: micro-wear analysis of quartz flake fragments. Journal of Archaeological Science: Reports 2, 517–531.
Kononenko, N., 2011. Experimental and archaeological studies of use-wear and residues on obsidian artefacts from Papua New Guinea. Technical Reports of the Australian Museum, Online 21, 1–244.
Lawn, B.R., Marshall, D.B., 1979. Mechanisms of microcontact fracture in brittle solids. In: Hayden, B. (Ed.), Lithic Use-wear Analysis. Academic Press, New York, pp. 63–82.
Lemorini, C., Plummer, T.W., Braun, D.R., Crittenden, A., Ditchfield, P.W., Bishop, L.C., Hertel, F., Oliver, J.S., Marlowe, F.W., Schoeninger, M.J., Potts, R., 2014. Old stones' song: use-wear experiments and analysis of the Oldowan quartz and quartzite assemblage from Kanjera South (Kenya). Journal of Human Evolution 72, 10–25.
Lerner, H., Du, X., Costopoulos, A., Ostoja-Starzewski, M., 2007. Lithic raw material physical properties and use-wear accrual. Journal of Archaeological Science 34, 711–722.
Levi Sala, I., 1996. A Study of Microscopic Polish on Flint Implements. B.A.R International Series. Tempus Reparatum. Oxford. vol. 629.
Madhavaraju, J., García y Barragán, J.C., Hussain, S.M., Pachaiveedu Mohan, S., 2009. Microtextures on quartz grains in the beach sediments of Puerto Peñasco and Bahia Kino, Gulf of California, Sonora, Mexico. Revista Mexicana de Ciencias Geológicas 26, 367–379.
Mansur, M.E., 1982. Microwear analysis of natural and use striations: new clues to the mechanisms of striation formation. In: Cahen, D. (Ed.), Tailler? Pour quoi faire: Prehistoire et Technologie lithique II, Recent progress in Microwear studies. Musée Royal de l'Afrique Centrale, Tervuren, pp. 213–233.
Mansur-Franchomme, M.E., 1983. Scanning electron microscopy of dry hide working tools: the role of abrasives and humidity in microwear polish formation. Journal of Archaeological Science 10, 223–230.
Mansur-Franchomme, M.E., 1986. Microscopie du matériel lithique préhistorique: traces d'utilisation, altérations naturelles, accidentelles et technologiques Cahiers du Quaternaire, 9. CNRS, Bordeaux.
Márquez, B., Baquedano, E., Pérez-González, A., Arsuaga, J.L., 2016. Microwear analysis of Mousterian quartz tools from the Navalmaíllo Rock Shelter (Pinilla del Valle, Madrid, Spain). Quaternary International (in press). http://dx.doi.org/10.1016/j.quaint.2015.08.052.
Marreiros, J., Mazzucco, N., Gibaja Bao, J.F., Bicho, N.F., 2015. Macro and micro evidences from the past: the state of the art of archeological use-wear studies. In: Marreiros, J.M., Gibaja Bao, J.F., Ferreira Bicho, N. (Eds.), Use-wear and Residue Analysis in Archaeology. Springer, pp. 5–26.
Martin, S., 2012. Mise en place d'une méthodologie d'analyse fonctionelle des industries en quartz en vue d'une application aux industries sur éclat du site de Payre (Ardèche). Master thesis, Dept. de Préhistoire. Muséun national d'Histoire naturelle, Paris.
Masson, A., Coqueugnoit, E., Roy, S., 1981. Silice et traces d'usage: le lustré des faucilles. Nouv. Arch. Mus. Hist. Nat, Lyon 19, pp. 43–51.
Meeks, N.D., Sieveking, G.d.G., Tite, M.S., Cook, J., 1982. Gloss and use-wear traces on Flint sickles and similar phenomena. Journal of Archaeological Science 9, 317–340.
Moncel, M.-H., Borel, A., De Lombera-Hermida, A., Sala, R., Deniaux, B., 2008. Quartz et quartzite dans le site de Payre (MIS 7 et 5, Ardèche, France) : données techno-économiques sur la gestion de roches locales au Paléolithique moyen. Comptes Rendus Palevol 7, 441–451.
Momber, A.W., 2015. A transition function for the solid particle erosion of rocks. Wear 328–329, 348–355.
Moss, E.H., 1983. The functional analysis of flint implements. Pincevent and Pont d'Ambon: two cases studies from the french final Palaeolithic. B.A.R. International Series vol. 177. Oxford.
Odell, G.H., Tringham, R., Roberts, M., Voytek, B., Whitman, A., 1976. Microwear analysis. Journal of Field Archaeology 3, 239–240.
OECD, 1969. Glossary of Terms and Definitions in the Field of Friction, Wear and Lubrication. Tribology. Research Group on Wear of Engineering Materials. Organisation for Economic Co-operation and Development (OCED), Paris.
Ollé, A., 2003. Variabilitat i patrons funcionals en els sistemes tècnics de Mode 2. Anàlisi de les deformacions d'ús en els conjunts lítics del Riparo Esterno de Grotta Paglicci (Rignano Garganico, Foggia), Áridos (Arganda, Madrid) i Galería-TN (Sierra de Atapuerca, Burgos). Ph.D. thesis, Dept. d'Història i Geografia. Universitat Rovira i Virgili, Tarragona, p. 589. Url: http://www.tdx.cat/TDX-0415108-171300.
Ollé, A., Mosquera, M., Rodríguez, X.P., de Lombera-Hermida, A., García-Antón, M.D., García-Medrano, P., Peña, L., Menéndez, L., Navazo, M., Terradillos, M., Bargalló, A., Márquez, B., Sala, R., Carbonell, E., 2013. The Early and Middle Pleistocene technological record from Sierra de Atapuerca (Burgos, Spain). Quaternary International 295, 138–167.
Ollé, A., Vergès, J.M., 2008. SEM functional analysis and the mechanism of microwear formation. In: Longo, L., Skakun, N. (Eds.), 'Prehistoric Technology' 40 Years Later: Functional Studies and the Russian Legacy. Proceedings of the International Congress Verona (Italy), 20-23 April 2005. B.A.R. International Series, vol. 1783. Archaeopress, Oxford, pp. 39–49.
Ollé, A., Vergès, J.M., 2014. The use of sequential experiments and SEM in documenting stone tool microwear. Journal of Archaeological Science 48, 60–72.
Pedergnana, A., Ollé, A., 2014. Use-wear and residues analyses on quartzite stone tools: setting up a methodology. In: Lemorini, C., Nunziante Cesaro, S. (Eds.), An Integration of Use-wear and Residue Analysis for the Identification of the Function of Archaeological Stone Tools". Proceedings of the International Workshop, Rome, March 5th-7th, 2012. B.A.R. International Series, vol. 2649. Archaeopress, Oxford, pp. 43–62.

Pedergnana, A., García-Antón, M.D., Ollé, A., 2016. Structural study of two quartzite varieties from the Utrillas facies formation (Olmos de Atapuerca, Burgos, Spain): from a petrographic characterisation to a functional analysis design. Quaternary International (in press). http://dx.doi.org/10.1016/j.quaint.2015.06.031.

Pedergnana, A., Ollé, A., 2016. Monitoring and interpreting the use-wear formation processes on quartzite flakes through sequential experiments. Quaternary International (in press). http://doi.org/.10.1016/j.quaint.2016.01.053.

Pignat, G., Plisson, H., 2000. Le quartz, pour quel usage ? l'outillage mésolithique de Vionnaz (Suisse) et l'apport de la tracéologie. In: Crotti, P. (Ed.), MESO'97. CAR, Lausanne, pp. 65–87.

Plisson, H., 1985. Étude fonctionnelle d'outillages lithiques préhistoriques pour l'analyse des micro-usures, recherche méthodologique et archéologique Ph.D. thesis, U.E.R. d'Art et d'Archéologie. Paris I, Paris, p. 357.

Plisson, H., Mauger, M., 1988. Chemical and mechanical alteration of microwear polishes: an experimental approach. Helinium XXVIII, 3–16.

Prost, D., 1990. Des enlèvements d'utilisation reproduits selon une méthode physique par percussion. In: Séronie-Vivien, M.R., Lenoir, M. (Eds.), Cahiers du Quaternaire. Éditions du C.N.R.S, pp. 513–519.

Richards, T.H., 1988. Microwear Patterns on Experimental Basalt Tools. B.A.R. International Series vol. S460. Oxford.

Rodríguez, X.P., De Lombera-Hermida, A., Fábregas Valcarce, R., Lazuén Fernández, T., 2011. The upper pleistocene site of Cova Eirós (Triacastela, Lugo, Galicia). In: De Lombera-Hermida, A., Fábregas Valcarce, R. (Eds.), To the West of Spanish Cantabria: the Palaeolithic Settlement of Galicia. B.A.R. International Series, vol. 2283. Archaeopress, Oxford, pp. 123–132.

Semenov, S.A., 1964. Prehistoric Technology. An Experimental Study of the Oldest Tools and Artifacts from Traces of Manufacture and Wear. Cory, Adams and Mackay Ltd., London.

Stemp, W.J., Lerner, H.J., Kristant, E.H., 2013. Quantifying microwear on experimental Mistassini quartzite scrapers: preliminary results of exploratory research using LSCM and scale-sensitive fractal analysis. Scanning 35, 28–39.

Sussman, C., 1988. A Microscopic Analysis of Use-wear Polish Formation on Experimental Quartz Tools. John and Erika Hedges Ltd., Oxford.

Taipale, N., 2012. Micro Vs. Macro. A Microwear Analysis of Quartz Artefacts from Two Finnish Late Mesolithic Assemblages with Comments on the Earlier Macrowear Results, Wear Preservation and Tool Blank Selection. Master thesis, Department of Archaeology and Ancient History. Upsala University.

Torcal, L., Tello, B., 1992. Análisis de sedimentos con Microscopio Electrónico de Barrido: exoscopía del cuarzo y sus aplicaciones a la geomorfología. Sociedad Española de Geomorfología. Geoforma Ediciones, Logroño.

Tringham, R., Cooper, G., Odell, G.H., Voytek, B., Whitman, A., 1974. Experimentation in the formation of edge-damage: a new approach to lithic analysis. Journal of Field Archaeology 1, 171–196.

Unger-Hamilton, R., 1984. The formation of use-wear polish on flint: beyond the "Deposit versus abrasion" theory. Journal of Archaeological Science 11, 91–98.

Van Gijn, A., 1990. The Wear and Tear of Flint: Principles of Functional Analysis Applied to Dutch Neolithic Assemblages. University of Leiden, Leiden.

Vaughan, P.C., 1985. Use-wear Analysis of Flaked Stone Tools. The University of Arizona Press, Tucson.

Williams, J.A., 2005. Wear and wear particles-some fundamentals. Tribology International 38, 863–870.

Witthoft, J., 1967. Glazed polish on flint tools. American Antiquity 32, 383–388.

Yamada, S., 1993. The formation process of "use-wear polishes. In: Anderson, P.C., Beyries, S., Otte, M., Plisson, H. (Eds.), Traces et fonction: Les gestes retrouvés. CNRS/Université de Liège, Liège, pp. 433–444.

Please cite this article in press as: Ollé, A., et al., Microwear features on vein quartz, rock crystal and quartzite: A study combining Optical Light and Scanning Electron Microscopy, Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.02.005