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Unveiling the behavioural significance of the Aterian coarse-grained lithic assemblages: Insights from use-wear analysis of Rhafas Cave, Northeast Morocco

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A R T I C L E I N F O

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A B S T R A C T

Recent discoveries have shown that *Homo sapiens* has a Pan-African origin, and North Africa has been an important region for the development and expansion of its biological and cultural traits. Early manifestations of *Homo sapiens* complex behaviour in North Africa are tied to the emergence of the Aterian culture around 150 ka BP. The Aterian repertoire includes stone, bone, and ivory tools, vegetal, animal and marine remains, as well as pigment and perforated shells for symbolic expressions. Within this cultural package, investigating the typo-technological variability observed in the stone tool assemblage is crucial to better understanding the emergence and development of *Homo sapiens* behaviour. However, the latter can only be fully reconstructed when complemented with the study of the tools' function.

Use-wear studies on Aterian lithics are very limited including coarse-grained materials despite their abundance in several Aterian sequences. This study presents the results of the use-wear analysis on the quartzite assemblage from the Aterian sequence of Rhafas cave. A use-wear experimental reference collection was created, against which the diagnostic use-wear on archaeological artefacts was compared. Sequential experiments demonstrated the dynamic performance and suitability of quartzite tools when subjected to mechanical stress during working of different materials.

The analysis of the archaeological assemblage, guided by the experimental reference collection, revealed diagnostic use-wear associated with wood and bone working.

In sum, our study shows the suitability, and the complementary role of quartzite tools in the technological versatility of the Aterian groups.

1. Introduction

Recent investigations into the origins of the *Homo sapiens* and its relationship with the emergence of the complex behaviour highlight the important contribution of the Northern African Middle Stone Age (MSA) archaeological record (Bouzouggar et al., 2007a, b; Bouzouggar and Barton, 2012; Dibble et al., 2013; Campmas et al., 2016). Until recently, this region has been much neglected despite the occurrence of key archaeological evidence, such as the early *Homo sapiens* remains (Hublin et al., 2017; Richter et al., 2017), and the oldest personal ornaments (Sehasseh et al. 2021). The main criteria of the complex behaviour in North Africa are tied to the emergence of the Aterian culture in the

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archaeological record around 150 ka BP. The *Aterian package* is marked by the appearance of bone tools (El Hajraoui, 1994; Bouzouggar et al., 2018; Hallet et al., 2021), pigment and shell beads (Vanhaeren et al., 2006; Bouzouggar et al., 2007a; d'Errico et al., 2009; El Hajraoui et al., 2012; Sehasseh et al., 2021), evidence of structured use of space (El Hajraoui, 2004; El Hajraoui et al., 2012; Bouzouggar and Barton, 2012) as well as vegetal and marine resource consumption (Campmas et al., 2016; Marquer et al., 2022).

Regarding lithics assemblages, recent petrographic and geo-chemical studies have shown the use of both local and non-local raw materials by the Aterian groups, including different varieties of chert and coarse-grained rocks (Wengler et al., 1998, 2006; Morala et al., 2012; Rafi, 2015, 2018). From a technological perspective, the Aterian lithic assemblages are marked by the introduction of blades, bladelets, and Kombewa technologies (Dibble et al., 2013; Spinapolice and Garcea, 2014), the use of soft hammer (Bouzouggar et al., 1997a, b; Bouzouggar et al., 2002; Spinapolice and Garcea, 2013), and bone retouchers (Turner et al., 2020; Hallet et al., 2021). Such technological novelty and variability seen within the Aterian lithic assemblages have been argued to reflect a flexible technology (Bouzouggar et al., 2007b; Bouzouggar et al., 2012).

Previous studies have provided valuable insights into the function of Aterian flint tools (Massussi and Lemorini, 2004/2005; Bouzouggar et al., 2007b; Tomasso and Rots, 2017; Falzetti et al., 2017; Tomasso and Rots, 2020; Tomasso et al., 2020; Tomasso, 2021, 2024). Furthermore, despite the abundance of coarse-grained raw materials at several MSA sequences (Texier, 1985–1986; Wengler et al., 1998, 2006; Rafi, 2015), these materials have yet to be subjected to any use-wear studies. This gap likely biases our overall understanding of these technologies, and the associated human behaviors tied to the origins of the Aterian industries.

The present study aims to contribute to filling this gap, by reporting the first use-wear analysis on Aterian quartzite lithic tools, from the archaeological site of Rhafas cave, Northeastern Morocco (Fig. 1).

For this study, an experimental protocol and reference collection have been combined, including fieldwork for selecting and collecting quartzite raw material matching those reported in the archaeological assemblages, experimental replications, and both macro and microscopic use-wear analysis. Different types of traces of use on quartzite were observed and studied at different microscopic scales, and during different phases (sequential experiments) and tasks (different motions and worked materials). Through experiments and use-wear analysis, this study aims to understand the formation of diagnostic macro and micro traces of use on quartzite lithic tools after processing different worked materials. Consequently, the results of these experimental replications were applied to study the lithic tools sampled from the Aterian assemblages from the sequence of Rhafas cave (Fig. 2). A new experimental protocol is ongoing to study the flint artefacts from the same assemblages from different archaeological sites. In the future, the comparison between these studies will allow access to the significance of different raw material types and their role within the Aterian techno-economy.

2. Use-wear studies on coarse-grained materials: A summary of the state-of-the-art

The so-called coarse-grained lithic raw materials encompass various types of rocks, such as quartz, and quartzite, which are commonly found in the archaeological record. In the archaeological literature, these rocks

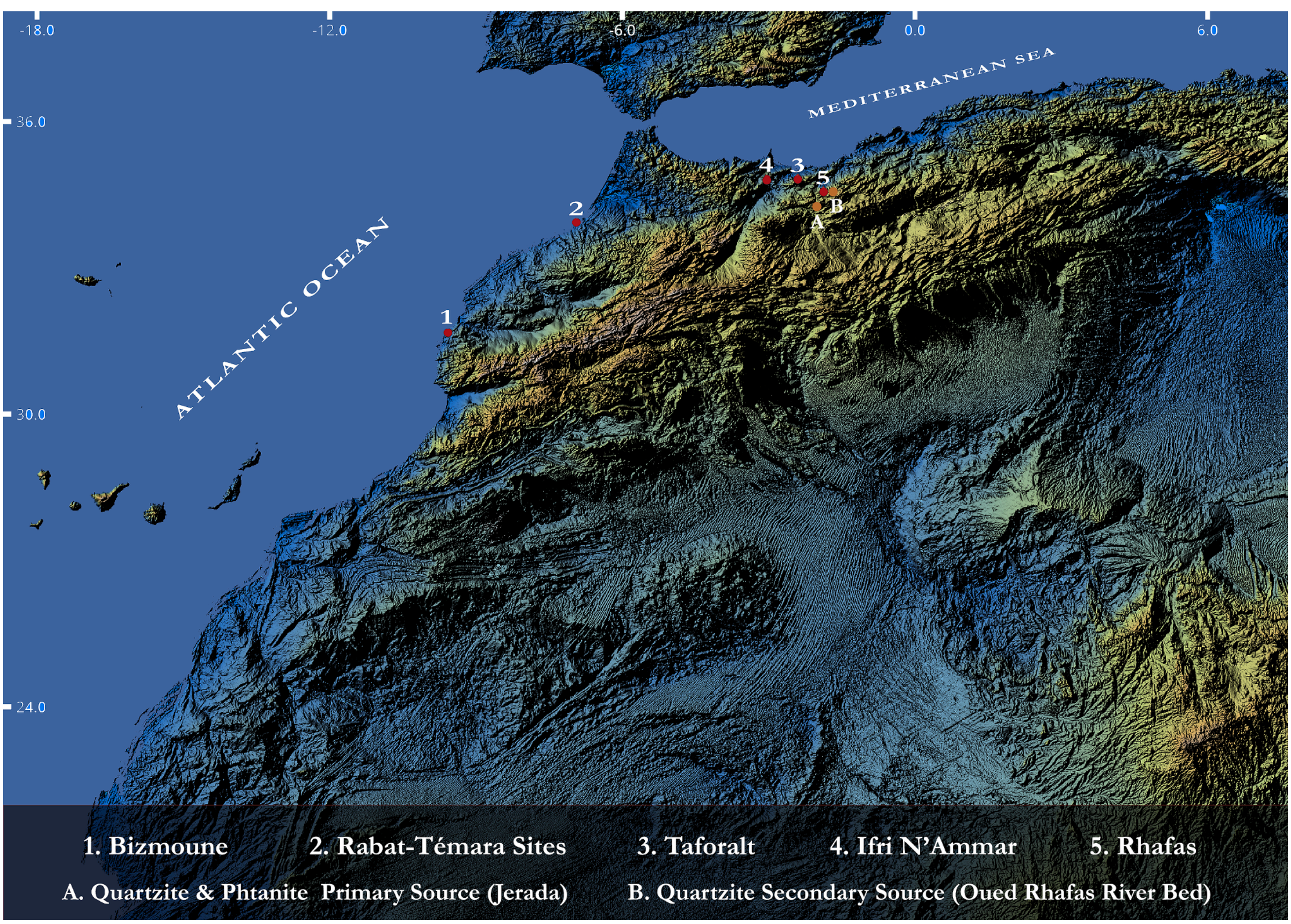

Fig. 1. Map showing the location of Rhafas cave (5), the quartzite raw material sources (A & B) and other key MSA sequences from Morocco.
source: Digital Elevation Model gathered from USGS: https://earthexplorer.usgs.gov/

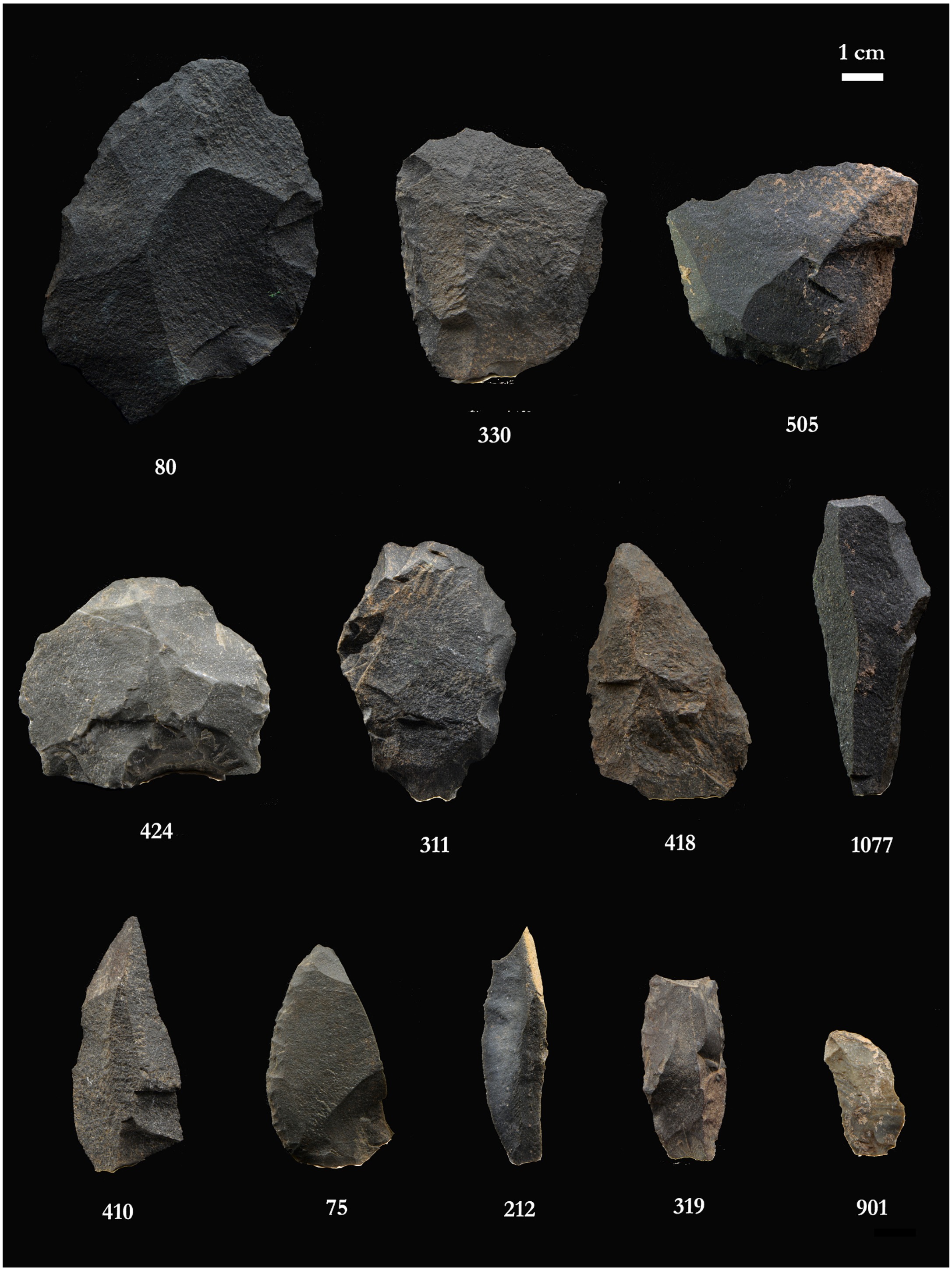

Fig. 2. Example of Aterian quartzite lithics from Rhafas cave (Layers 3a & 3b). 80 Side scraper; 330 Side-scraper; 505 Flake; 424 End scraper; 311 Side-scraper; 418 convergent scraper; 1077 Side-scraper; 410 Point; 75 Convex side-scraper; 212 naturally Backed knife; 319 Convex side-scraper; 901 Bladelet.

are described as being formed by macro-crystalline quartz with significant structural differences including the mineralogical composition, grain size, and orientation (e.g., Grace, 1990; Clemente Conte and Gibaja, 2009; Ollé et al., 2016).

Although present among Pleistocene lithic assemblages, coarse-grained materials have generally been poorly investigated in use-wear studies when compared with fine-grained rocks, such as flint. In general, in use-wear studies, more efforts have been made to set up solid methodologies to study chert artefacts (e.g., Semenov, 1964; Tringham et al., 1974, Keeley, 1980; Vaughan, 1985; Mansur-Franchomme, 1986; Van Gijn, 1990; Gonzãlez Urquijo and Ibãnez Estévez, 1994), due to their abundance in the archaeological record and their feasibility for examination under the optical microscopes with no need for extra light filter or specific imaging techniques (Clemente Conte and Gibaja, 2009; Ollé et al., 2016; Pedergnana, 2017). Coarse-grained raw materials, however, have been always considered difficult to study at the microscopic scale (Beyries and Roche, 1982; Plisson, 1985; Grace, 1990; Borel et al., 2014) mainly due to the irregular surface microtopography and high surface reflectivity (e.g., Sussman, 1985; Grace, 1990; Igreja, 2009; Clemente Conte and Gibaja, 2009).

Additionally, use-wear terminology is still poorly uniform while dealing with coarse-grained materials. This can be justified by several factors such as the direct analogies between use-wear on flint and coarse-grained rocks, the structural variabilities of the latter, and the personal description of each analyst (Grace, 1996). Although an equivalent categorization of use-wear types is employed on different raw materials (Clemente Conte et al., 2015), the use of the same term to describe different use-wear features and vice versa has been observed in several cases (Ollé et al., 2016). Moreover, the use of some terms and definitions based on different microscopes and magnifications has also contributed to this confusion.

During the last decades of use-wear studies, alternative microscopy methods and imaging techniques have been suggested to overcome these difficulties while dealing with coarse-grained materials, such as the use of differential interference contrast (DIC) (e.g. Igreja, 2009; Cristiani et al., 2009; Galland, 2022), the replacement of the original surfaces and edges by positive resin casts (Banks and Kay, 2003), or the use of negative silicon moulds (Lemorini et al., 2014; Venditti, 2014). Additionally, several analysts have preferred scanning electron microscopes (SEM) for the study of coarse-grained raw materials. This imaging technique allows high-quality micrographs due to the wide depth of field and high-power magnification. Thus, more detailed observation and documentation of the use-wear and post-depositional traces on rough micro surfaces have been acquired (Sussman, 1985, 1988; Knutsson, 1988a; Knutsson and Lindé, 1990; Ollé and Vergès, 2008, 2014; Borel et al., 2014; Clemente Conte et al., 2015; Ollé et al., 2016; Pedergnana and Ollé, 2017; Pedergnana, 2019). Recently, the quantification of the use-wear traces, using laser scanning confocal microscopy (LSCM) and surface texture analysis, has provided very promising results for the classification and characterization of micro use-wear traces on the surface of coarse-grained raw materials (e.g., Pedergnana et al. 2020). These innovative techniques, when applied to experimental and archaeological artefacts can contribute to a better understanding of the formation of use-wear traces and therefore provide better discrimination of the processes involved in their formation (motion, worked material, etc.) (e.g., Evans et al 2014; Stemp et al, 2018; Calandra et al. 2019). This, due to the above-mentioned aspects, is particularly relevant for quartzite, which is very abundant in several Pleistocene and Holocene archaeological assemblages (Kamminga, 1982; Carbonell et al., 1999; Márquez et al., 2001; Ollé, 2003; Gibaja et al. 2002; Gibaja and Carvalho, 2005; Gibaja et al., 2009; Cristiani et al., 2009; Lemorini et al., 2014; Pedergnana et al., 2018; Lemorini et al., 2019; Pedergnana and Ollé, 2020; Knutsson, 1988b; Taipale et al., 2014).

3. The archaeological site of Rhafas cave

3.1. History of archaeological works at Rhafas cave

Rhafas Cave (34°33′28′'N, 1°52′26′'W) is located 15 km south of the city of Oujda, approximately 60 km south of the Mediterranean Sea and at an elevation of around 900 m above current sea level (Wengler, 2001). It is a simple dome-shaped dissolution feature within the local dolomitic limestone, opening to the south-east, and situated on the north-western slope of a prominent northeast/southwest trending valley (Wengler, 1993a,b; Wengler et al., 2006). The cave was discovered by Jean Marion in 1950, and the first description of the lithic assemblages was provided by Roche (1963). Two systematic series of excavations were undertaken by Luc Wengler (1979–1986 & 1900s) in the interior of the cave with 39 of 71 layers showing evidence of human occupation, divided into four main units (Fig. 3) (Wengler, 2001). Stratigraphically, the bottom, unit IV (levels 71 & 70) consists of brecciated sediment with cobbles, followed by ~ 3 m unit III (Layers 7 to 68), characterized by accumulated sandy silts interbedded with thin calcareous levels and overlayed by sandy loamy matrix. Unit II (Layers 6 to 2) consists of sediments rich in refracted platelets and the bottom and chalk crust soil towards the upper part of Layer 3, and Unit I contain sandy sediments (Wengler, 2001; Wengler et al., 2006). The combination of the chronological (radiocarbon and luminescence dating) and cultural material studies showed an MSA occupation between ~ 100 (Layer 6d) and 70 Ka (Layer 3a), followed by a Neolithic occupation at Layer 1, Unit 1, with a C-14 date of 5963 ± 150 cal BP (Mercier et al., 2007).

A new series of excavations, initiated in 2007, focused on both the interior of the cave and the terraced area at its entrance. During this program, Wengler's original stratigraphic framework and numbering system were retained, despite the loss of the original section line due to erosion and subsequent excavations. To enhance the stratigraphic understanding, two additional reference profiles were established: one describing the cave mouth area and the second addressing the lower cave infill.

3.2. Chronostragraphic sequence of Rhafas cave

The new revision of the chronostratigraphic sequence was undertaken based on optically stimulated luminescence (OSL) dating on sand-sized quartz grains, combined with geological and sedimentological analyses. The upper section of the sequence (Layer 4c to 1) revealed an early Middle Stone Age (MSA) occupation, in Layer 4c, dated to ~ 135.3 ± 10.3 Ka, followed by an age of ~ 108.5 ± 9.9 ka in Layer 3b.

Layer 3a yielded ages of 85.4 ± 4.5 ka and 98.5 ± 19.8 ka, and a later MSA occupation was identified in the terrace section in Layer S5, dated to ~ 56.9 ± 3.5 ka. Excavations of the terrace area also uncovered evidence of Later Stone Age (LSA) occupations, represented in Layers S3 (~21.4 ± 1.4 ka) and S2 (~15.4 ± 1.2 ka). Additionally, an early Neolithic occupation was identified in Layer 1 of the cave mouth section, dated to ~ 7.8 ± 0.6 ka (Doerschner et al., 2016).

The lower section of the Rhafas cave, yielded a lithic assemblage previously attributed to the MSA (Wengler, 1993a). However, these deposits remain undateable due to inconsistencies in radioactive dose rates, mainly the increase of radioactive elements (e.g., potassium). This increase is likely caused by groundwater percolating through the surrounding rocks, mobilizing radioactive materials, and depositing them in the sediments, thus rendering age calculations unreliable (Doerschner et al., 2016).

3.3. Quartzite raw material sourcing and distribution at Rhafas cave

At Rhafas cave, the petrographic studies on lithics revealed the presence of varied raw materials, collected from both primary and secondary sources, and covering a radius of more than 80 km around the site (Wengler, 1993a, Wengler et al., 2001; Wengler et al., 2006) (Table 1).

However, only a few types of rocks showed a continuous presence throughout the sequence, including flint, chalcedony, and quartzite (Wengler, 1993a). Within the MSA layers, certain coarse-grained materials (e.g., quartzite) are found to be consistently occurring, and at certain levels, showing higher frequency than chert (Wengler, 1993a, b; Wengler et al., 2006; Longet, 2023). In the landscape surrounding the site, metaquartzite is found in Paleozoic deposits (Wengler, 1993a, b; Wengler et al., 2006). Its occurrence is attributed to the regional and contact metamorphism factors. This is evidenced by the minerals' structure and orientation, the presence of neoformed minerals, indicating the thermal effect as well as the existence of the metamorphosed rocks in proximity to the granitic ones**.** Quartzite is mostly found in primary sources associated with other rocks such as phtanite and sandstone, or in secondary ones (e.g., riverbeds, and terraces) worn into pebbles by natural processes (Longet, 2023).

3.4. MSA lithic typo-technology at Rhafas cave

The Middle Stone Age (MSA) lithic industry of the Rhafas sequence is characterized primarily by the production of flakes and elongated blanks. Edge modifications are highly frequent within all layers,

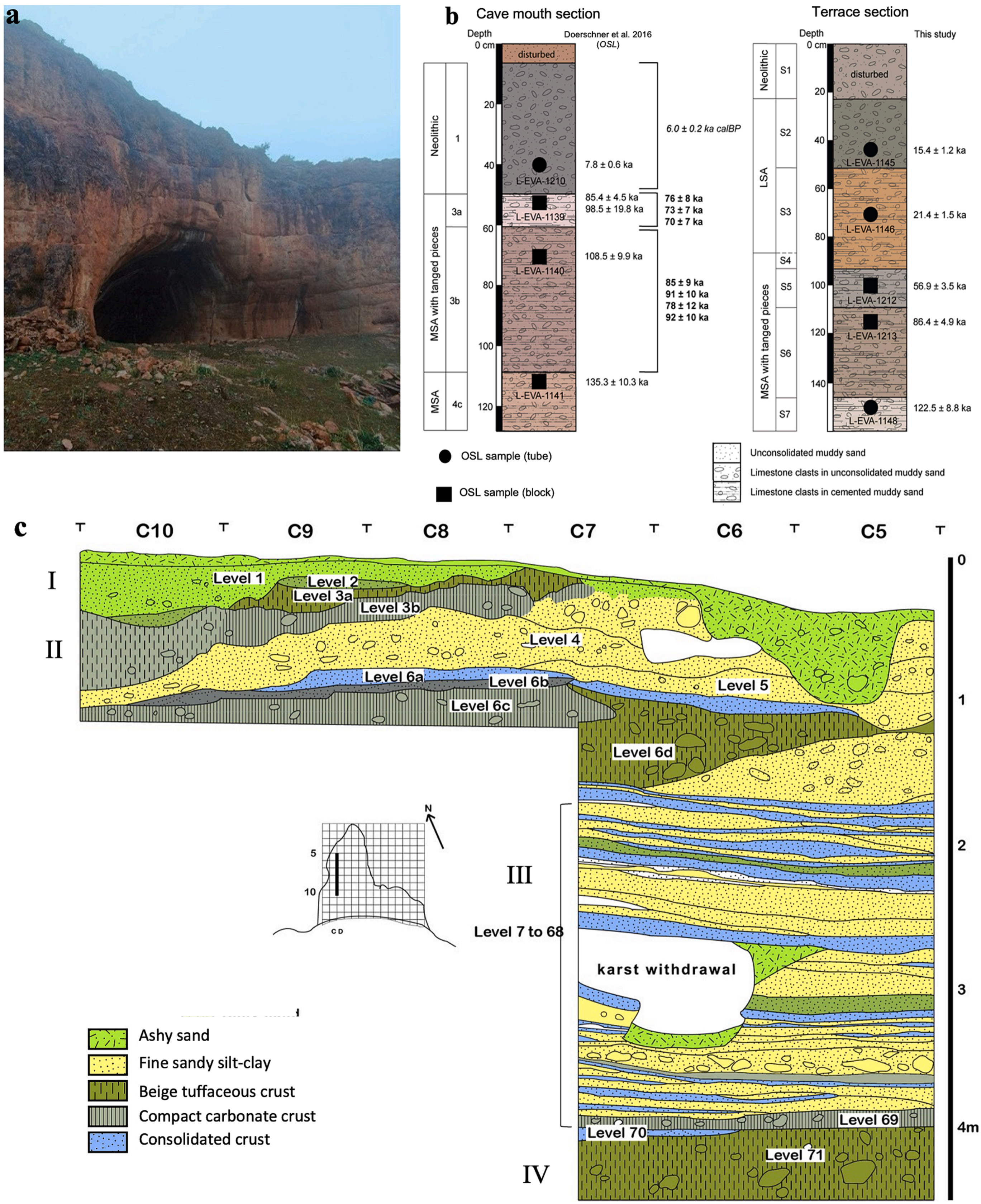

Fig. 3. Chrono-stratigraphy of Rhafas cave. a. Photo of the cave; b. chronology of the cave mouth and the terrace layers using OSL dating on sand-sized quartz grains (Modified after Doerschner et al., 2016); c. Full stratigraphy of Rhafas cave (Modified after Wengler et al., 2006 and Longet et al., 2023).

Table 1
Raw material distribution (percentual representation) from Rhafas cave, modified after Longet, 2023 and (Longet et al., unpublished results).

	Layer 6	Layer 5	Layer 4c	Layer 3b	Layer 3a
Phtanite	32.6	37.9	41.4	24.6	44.3
Quartzite	27.9	10.7	12.6	9	5.4
Tuffite	12.5	23.4	13.3	20	19
Chalcedony O. el Haÿ	4.7	3.4	6.2	10.6	4.8
Chalcedony Trias	3.6	4.6	4.5	12.2	5.2
Chert	10.4	13.8	3	6.3	8.8
Other	8.3	6.2	18.8	17.3	12.5
Total	100	100	100	100	100

resulting in the production of different stone tools that characterize the MSA in Northern Africa (Bordes, 1979).

Throughout the MSA sequence, more than 20 % of the blanks exhibit edge modifications on one or more edges, except in layer 4c. Additionally, simple side-scrapers are the most represented tool types within all layers, ranging between 43.8 % and 58.2 % (Longet, 2023).

In lower layers (6 and 5), the blank preparation is predominant by dihedral (51.3 %) and faceting (46.8 %). In contrast, the upper layers (4 to 3a) exhibit a more equal distribution among plain, dihedral, and faceted preparation techniques.

In lower layers (6 and 5), the blank preparation is predominant by dihedral (33.7 % in L6, 23.3 % in L5) and faceting (23.2 % in L6, 37.2 % in L5).

The lithic assemblages of the Rhafas cave can be divided into two main technical groups distinguished by the operational sequences, the production intentions, and the presence of specific tools (Wengler 1993a; Wengler et al.,2001; Wengler et al., 2006; Longet, 2023). From the technological perspective, the Rhafas MSA shows a progressive evolution of technical systems through the sequence (Longet, 2023; Longet et al., *unpublished results*).

The first technical group is defined in layers 6 to 4, characterized by the production of flakes, scarcity of laminar blanks, and the high diversity of side-scrapers' types. Blanks from these layers are mainly obtained either from inclined or parallel cores (Conard et al., 2004), often Levallois.

The second group, layers 3b to 2, is characterized by laminar and lamellar technologies, the presence of retouched tools (e.g., side-scrapers, notches, end-scrapers) and the occurrence of specific artefacts such as bifacial foliates and tanged pieces. Although Levallois methods are also present in these layers for the flakes and elongated blanks production, volumetric methods are notably documented.

Quartzite raw material is used in different technical systems including the Levallois, micro-Levallois, and laminar and lamellar technologies (Wengler, 1993a; Longet, 2023). Therefore, it remains crucial to understand the role of this lithic raw material within the techno-economy of the Aterian groups of Rhafas cave based on the use-wear analysis.

4. Materials and methods

4.1. Experimental protocol and reference collection

4.1.1. Raw material selection

In this study, quartzite samples for experimental replications have been sourced from two locations; a primary Paleozoic deposit that lies ~ 30 km from the cave and a secondary source (riverbed) situated at ~ 900 m (Fig. 1). The selected samples were used to produce experimental tools (n = 17) by one of the authors (Y.D) using a hard hammer and direct percussion. Unretouched flakes were used during the experiments to improve the documentation and analysis of the different modifications on the tool's edge and surface at both the macro and micro scales of analysis. This is also aimed at minimizing the effect and misleading interpretations between technological retouch and edge damage (use-wear macro and micro-scars or edge scarring) resulting from use. All experimental flakes were kept in separate plastic bags to prevent any edge or surface damage beyond what resulted from the material processing during the experiments (Anderson-Gerfaud et al., 1987).

4.1.2. Experimental design

Experiments included a total of 57 cycles (interval of use) in which both longitudinal (sawing and cutting-like motions) and transversal (scraping-like movements) motions were applied to hard (n = 2) and soft (n = 2) worked materials (Fig. 4). Experimental samples were used with unidirectional movements (one stroke per movement) for scraping and cutting tasks, and bidirectional movements (two strokes per movement) during sawing, depending on the worked material. Each tool was used for an individual motion on a single worked material, for a determined duration (see more details in Table 2). The contact angle between the stone tool edge and the worked material was, as much as possible, the same, despite the unintentional change in some cases due to the experimenter's hand muscle fatigue. Four different contact materials were processed during the experiments, wood (fresh and dry), animal hard material, animal hide, and meat (Table. 2). Wood samples (*Cedrus atlantica*) were collected from Ain Almou, Beni Snassen region, ~50 km from Rhafas cave. Although previous works did not report its presence at the studied site (Wengler and Vernet, 1992), a recent anthracological study at Taforalt cave, situated in the same region (~ 70 km), indicated its presence within the MSA sequence (Bouzouggar et al., 2007a). The wood branches (n = 6) were collected in November (autumn) and divided into two groups, fresh (n = 3) processed directly after their removal, and dry (n = 3) processed in the next August (summer).

Bos taurus ribs (n = 4) were selected for sawing and scraping motions at dry and fresh states. We selected the ribs because they are known to be the main blank of the bone tools with Aterian assemblages (El Hajraoui and Debénath, 2012; Bouzouggar et al., 2018; Hallet et al., 2021). Fresh bone samples (n = 2) were processed less than 24 h after their removal from the animal body and the hard bone samples (n = 2) were exposed for 5 weeks before the beginning of experiments.

The experimental flakes used for hard materials (bone and wood) processing were analysed over the course of 5 sequential sessions, with different modifications documented before and after each session of use. *Sus scrofa*'s (n = 1) fresh hide was suspended on a frame using strings to avoid the tool contact with the ground. We used 5 flakes for cutting (n = 2) and scraping (n = 3) the hide to remove the remains of fat and meat. Experimental flakes (n = 2) were used to cut 1 kg of *Bos taurus* meat into small pieces to check the impact of the soft materials process on the quartzite.

All experiments were done by a single person (Y.D.), during which the flakes were used while held in the hand. Edge performance was described directly after each use, which, in this study, was assessed by visually describing the suitability of the tool for the task, the progress of the worked material processing and the degree of the edge fragmentation based on the description of the removed micro-flakes (i.e., edge damage). During the sequential experiments, different modifications on active edges were described and recorded microscopically after different intervals of use.

4.1.3. Archaeological sampling for use-wear analysis

The sampling of the archaeological lithics was carried out at the National Institute of Archaeological Sciences and Heritage (INSAP), Morocco, where the material from Rhafas is stored. All samples (n = 135) were selected from the Aterian assemblages of the MSA sequence of Rhafas cave (layers 3a and 3b) from the recent excavations between 2007 and 2010 (Bouzouggar et al., 2019). The selected group of artefacts included different items representative of the different technological categories, as well as retouched and unretouched tools (following the protocol suggested by Marreiros et al. 2020). From the total of 135

Fig. 4. Examples of the experimental activities for the creation of the reference collection: a) sawing dry wood (*Cedrus Atlantica*); b) scraping *Bos taurus* fresh bone (rib); c) scraping fresh *sus scrofa*'s hide to remove fat and meat.

Table 2
Experimental samples, worked materials, and different parameters used in the sequential experiments.

ID	Raw Material	Worked material	Worked material type	Hardness degree	Motion	Movement	Contact angle	Duration (min)
QTZ-W1	Quartzite	Dry wood	*Cedrus atlantica*	Hard	Sawing	Longitudinal-bidirectional	~ 90°	5–15-30–45-60
QTZ-W2	Quartzite	Fresh wood	*Cedrus atlantica*	Hard	Sawing	Longitudinal-bidirectional	~ 90°	5–15-30–45-60
QTZ-W3	Quartzite	Dry wood	*Cedrus atlantica*	Hard	Scraping	Transversal-unidirectional	$30° < x < 45°$	5–15-30–45-60
QTZ-W4	Quartzite	Fresh wood	*Cedrus atlantica*	Hard	Scraping	Transversal-unidirectional	$30° < x < 45°$	5–15-30–45-60
QTZ-W5	Quartzite	Dry wood	*Nerium oleander*	Hard	Sawing	Longitudinal-bidirectional	~ 90°	5–15-30–45-60
QTZ-W6	Quartzite	Dry wood	*Nerium oleande*	Hard	Scraping	Transversal-unidirectional	$30° < x < 45°$	5–15-30–45-60
QTZ-B1	Quartzite	Fresh bone	*Bos taurus*	Hard	Sawing	Longitudinal-bidirectional	~ 90°	5–15-30–45-60
QTZ-B2	Quartzite	Dry bone	*Bos taurus*	Hard	Sawing	Longitudinal-bidirectional	~ 90°	5–15-30–45-60
QTZ-B3	Quartzite	Fresh bone	*Bos taurus*	Hard	Scraping	Transversal-unidirectional	$30° < x < 45°$	5–15-30–45-60
QTZ-B4	Quartzite	Dry bone	*Bos taurus*	Hard	Scraping	Transversal-unidirectional	$30° < x < 45°$	5–15-30–45-60
QTZ-H1	Quartzite	Fresh hide	*Sus scrofa*	soft	Scraping	Transversal-unidirectional	$30° < x < 45°$	30
QTZ-H2	Quartzite	Fresh hide	*Sus scrofa*	soft	Scraping	Transversal-unidirectional	$30° < x < 45°$	30
QTZ-H3	Quartzite	Fresh hide	*Sus scrofa*	soft	Scraping	Transversal-unidirectional	$30° < x < 45°$	30
QTZ-H4	Quartzite	Fresh hide	*Sus scrofa*	soft	Cutting	Longitudinal-unidirectional	~ 90°	30
QTZ-H5	Quartzite	Fresh hide	*Sus scrofa*	soft	Cutting	Longitudinal-unidirectional	~ 90°	30
QTZ-M1	Quartzite	Raw meat	*Bos taurus*	soft	Cutting	Longitudinal-unidirectional	~ 90°	10
QTZ-M2	Quartzite	Raw meat	*Bos taurus*	soft	Cutting	Longitudinal-unidirectional	~ 90°	10

items, 40 were selected (20 from each layer) to be submitted for a detailed use-wear analysis based on three standard main criteria: (1) the presence of one or more active edges (2) the preservation state (complete or partially complete edges and absence of heavy patination), and (3) the presence of macro and micro-wear, which was performed by comparing them to the experimental reference collection that was created.

This initial selection was done using a binocular stereomicroscope (JEULIN, with magnifications from 20x to 50x, including eyepiece) and a Nikon Eclipse LV100ND optical upright microscope (5x, 10x and 20x objectives). After the initial study, a further in-depth use-wear analysis was carried out at TraCEr, Laboratory for Traceology and Controlled Experiments, in Germany.

4.2. *Cleaning protocol (experimental and archaeological samples)*

After each experiment, all samples were submitted to a uniform cleaning protocol after each use step to remove the organic residues of different worked materials before documentation and analysis. Each flake was soaked in a polythene minigrip bag with a 1 % solution of fatty alcohol alkoxylate Plurafac^{R}LF-901. The bags were placed into an ultrasonic tank filled with tap water heated at 45 °C. To avoid any physical contact with the metal walls and base of the tank, the bags were suspended horizontally on the tank's edge with a clamp and were left for 5–10 min to adjust to similar water temperatures (Pedergnana and Ollé., 2017; Schunk et al., 2023) (Fig. 5). Each tool was submitted to a 10–15-minutes bath, followed by 3 times cleaning with distilled and tap water. To clean the sample used to process collagenous materials (e.g., bone, meat, hide), the fatty alcohol alkoxylate Plurafac^{R}LF-901 was replaced by a 150 ml 0.5 M NaOH solution, to remove the residues stuck on the edge.

Regarding the archaeological artifacts, each sample was placed in a polythene minigrip containing 150 ml of distilled water and processed in the ultrasonic tank following the same protocol used for the experimental tools.

For samples exhibiting residues on the proximal and/or non-active edges, they were individually suspended in the ultrasonic tank using a retort stand to preserve the residues identified during the preliminary diagnostic.

4.2.1. *Use-wear traces description and terminology*

The use-wear results reported in this study are fully based on optical

Fig. 5. Ultrasonic basin and the chemical products used for cleaning the experimental samples.

microscopic observations and analysis. Therefore, the description of the different use-wear traces is based on the general terminology used for chert materials (Semenov, 1964; Tringham et al., 1974; Keeley, 1980; Vaughan, 1985; Plisson, 1985) adding some specific aspects from the study of quartzose rocks (Kamminga, 1979; Knutsson, 1988a, b; Sussman, 1988; Ollé et al., 2016). Such an approach will also be crucial when the ongoing study of the flint artefacts is concluded, and data can be compared. In this study, we used the contact angle (also described by other colleagues as the *angle of attack*) to describe the angle between the tool's edge and the surface of the worked material.

During the use-wear description, the term macro-scar is used to refer to the conchoidal fracture visible on the edge by the naked eye and at low magnification, and micro-scar is used to describe the same edge scarring observed microscopically on the ridges of the quartz crystals present on the quartzite's surface. Although edge rounding is a term in use-wear analysis for the diagnostic identification of worked materials hardness, the contact angle, and the kinematic determinations (Keeley, 1980; Anderson-Gerfaud, 1981; Vaughan, 1985; Plisson, 1985), from our perspective, it fails to fully describe the bluntness of an edge that results from micro-flakes removals. This inadequacy is due to the term's restriction to the description of a rounded form, while the bluntness of an edge may take on various shapes. Therefore, we replaced it with the term blunt edge/edge bluntness, which refers to the sharpness loss, and associated it with the shape description (bevelled, round, and flat). At the microscopic scale, edge bluntness is applied to describe the same use-wear developed on the crystal sides.

Striations are the linear marks created on the tool surface, and their formation could be due to manufacture (Rots, 2010), use (Semenov, 1964; Keeley, 1980), or post-depositional factors (Mansur, 1982; Shea and Klenck, 1993; Levi-Sala, 1986; Burroni et al., 2002; Evans and Donahue, 2005; Caux et al., 2018).

Although various classifications have been proposed to describe striations using different terminologies (Semeneov, 1964; Keely, 1980; Kamminga, 1979, 1982; Masur-Franchomme, 1986; Knutsson et al., 1988; Sussman, 1988; Taipale, 2012), the most widely accepted system categorizes them into two groups (sleeks and furrows) which was adopted in this work. Sleeks are described as fine striations characterized by a smooth and regular margin (Mansur, 1982; Sussman, 1988; Mansur-Franchomme, 1986) caused by plastic deformation (Kamminga, 1979, 1982; Levi-Sala, 1996; Knutsson et al., 1988; Fullagar, 2006; Taipale, 2012), and furrows as the large, rough (Mansur, 1982; Mansur-Franchomme, 1986; Sussman, 1988; Fullagar, 2006), and irregular ones (Kamminga, 1982; Knutsson, 1998; Taipale, 2012).

The micro-polishes were qualitatively categorized and described following such well-established terms and criteria as texture, extension/contour, orientation, and distribution (Keeley, 1980; Plisson, 1985; Vaughan, 1985; Masur-Franchomme, 1986). We used crystal mechanical abrasion, to describe the mechanical alterations occurring on the crystal's ridges (gradual abrasion), and surface (pits). In prior research, this alteration was referred by different terms (e.g., crystal corrosion), and was explained by the loss, disappearance, or dissolution of a part of the original crystal's surface (Leipus and Mansur, 2007; Gibaja et al., 2009; Clemente Conte and Gibaja, 2009; Clemente Conte et al., 2015).

The term micro-flakes is used to describe the particles detached from the edge due to the frictional contact with the worked material, and to follow the edge performance changes, we used high and low performance to describe how effectively the edge contact with the worked material leads to progress within the applied task.

The quartz crystals on the experimental samples were described microscopically before (shape, micro-topography, possible technological wear) and after each interval of use (use-wear: e.g., striations, micro-scars). Additionally, the micro-flakes removed from the edge have been collected and observed microscopically under the Digital microscope (SmartZoom 5) after each use. We aimed by this step to combine the removed micro-flakes and the edge scarring to better understand the mechanical processes related to the formation of traces of use, particularly edge damage and surface abrasion, and how these related to the quartzite physical properties, such as brittleness (Knutsson, 1988a). Additionally, different changes in experimental tools have been recorded using the sequential experiment (Yamada, 1993; Ollé and Vergès, 2008; 2014; Ollé et al., 2016). Edge modifications have been monitored before and after a determined duration of use (Table 2).

4.2.2. Imaging analysis

In this study, one of the objectives is to evaluate the developed imaging analysis on the archaeological samples. This was done by comparing different use-wear and examining the extent to which, the optical microscope can be employed for the study of the coarse-grained rocks, including the worked material determination. Therefore, the use-wear analysis of the surfaces and edges of the archaeological samples were examined at complementary scales combining both low and high-magnification observations and documentation. Macro observations were carried out using a 3D digital microscope (ZEISS Smartzoom 5, 1.6x objective). Microscopic areas were analysed using a reflected light microscope (ZEISS Axio Scope.A1 MAT, objective EC Epiplan 5x/0,13 M27, EC Epiplan 10x/0.25 M27, Objective EC Epiplan 20x/0.4 M27 and Objective EC Epiplan 50x/0,75 M27) (see Supplementary data 1 for more details on equipment settings and data acquisition). During the observation and analysis, all images were acquired with the dedicated software ZEISS Zen Core, using the image Extended Depth of Focus (EDF) stacking module to generate in-focus images. The selection of use-wear imaging mode (black & white/color mode) was chosen in each case depending on the degree of development and visibility of the different use-wear traces. Due to the mineral characteristics of the quartzite surfaces (especially its reflectiveness), it is difficult to systematically use the same acquisition settings for all documented surface areas. Digital images, including overviews, areas of interest, and specific surface macro and micro features, were edited using GIMP (a free and open-source image editor) after acquisition (available at https://www.gimp.org, version 2.10.18). Inkscape (a free and open-source vector graphics editor, available at https://inkscape.org, version 0.92.4) was used to combine different pictures in a single frame.

5. Results

5.1. Experimental collection: Use-wear formation and descriptive inferences on the performance of quartzite tools

In this experimental study, 17 unretouched quartzite flakes were used on a total of 57 tasks, in which 4 worked materials were processed, using 3 different motions (see details in Table 2). Combining the sequential experiments with the description of the detached micro-flakes aimed at understanding and documenting the formation process of the different macro and micro use-wear traces on the quartzite samples. Throughout the experiments, the quartzite flakes showed different degrees and types of use damage, identified at the different stages of use depending on the hardness of the worked material and the applied motion. Based on our observations, the flakes used to work on hard materials, such as bone and wood, demonstrated higher performance during the transversal motions. During this task, micro-flakes were detected detaching from the tool's edge already since the first 5 min of use. After 15 min of use, the number and size of the removed micro-flakes remarkably increased, followed by a gradual decrease after 30 min. Our observations during the experiment show that this process led to edge stability, meaning less damage on the tool's edge (Fig. 6).

The same main process was observed during sawing motions. However, the lithics used for this task showed less performance due to the continuous attrition as the result of the tool's edge contact with the two lateral slopes of the cut made into the contact material. Additionally, the intensive loss of micro-flakes with bigger size and quantity led to a quick edge dulling. Regarding the work of soft materials, such as hide and meat, the cutting motion demonstrated a higher performance than

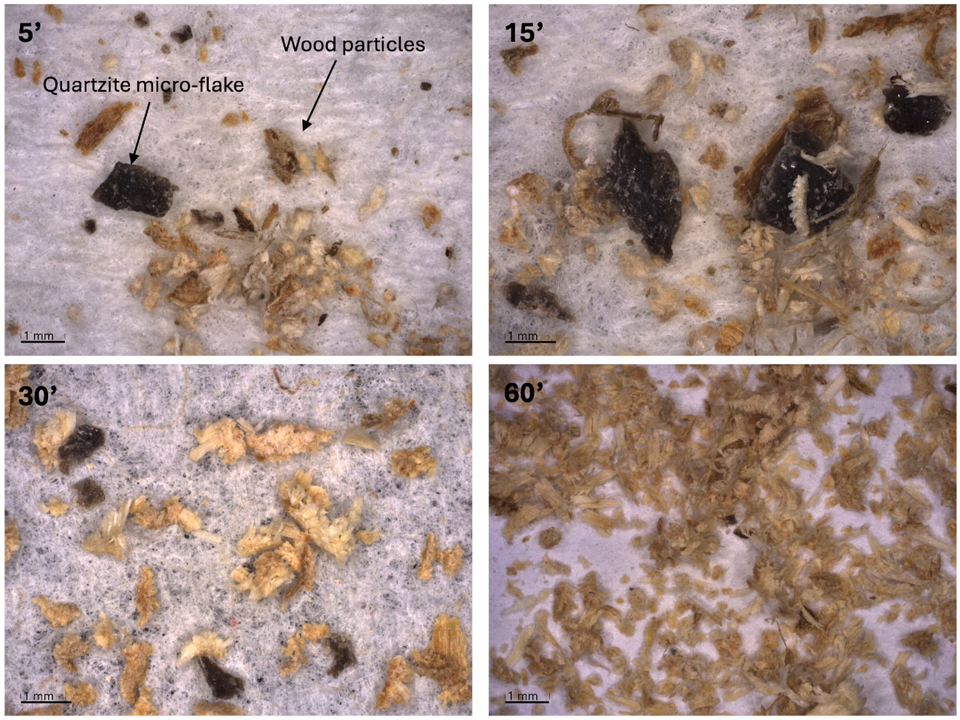

Fig. 6. Micro-flakes detached from the active edge due to *Nerium oleander* hardwood scraping (Sample QTZ-W6). a. 5 min, b. 15 min, c. 30 min, d. 60 min.

scraping. Unfortunately, we did not manage to recover the micro-flakes after their removal, since the experiment has been carried out in the field.

Although observations were made using the combination of low and high magnifications, main changes on the edge were however only detected when using the 10x, 20x and 50x optical objectives. However, the high reflectivity and irregular micro-topography made the use-wear identification and documentation, in several cases, very difficult, especially at x50 optical objective.

In terms of the formation process of micro traces on the quartzite's surface, before the use of the samples, two different types of quartz crystals have been identified and described microscopically. The first (Type 1) is characterized by a prominent surface and irregular micro-topography, making it easier to break and detach from the edge due to the consistent pressure and friction with the worked material. On the other hand, the second (Type 2) is very cemented, and characterized by a flat surface and less reflection (Fig. 7). From our microscopic observations and comparison between the observations during the sequential experiments, each type of microcrystal reacts differently to the worked materials processing. With hard materials, crystals (Type 1) are either partially or completely removed from the edge after the first few minutes of use. However, the intensive use of the edge on hard materials has shown a relative flatness and, in some cases, plastic deformation, and use-wear formation (e.g., striations). For instance, Fig. 8 shows the same mechanical process on two different crystals due to dry wood processing; the crystals lose the protruding parts of the edge, which leads to a relative flatness of their surface followed by long sleeks formation. On the other hand, the flat crystals (Type 2) demonstrated a higher level of resistance towards the hard materials process. Their fragmentation degree varied from the formation of a few micro-scars and striations on the crystal's ridges and surface to the total breakage and removal depending on factors such as the crystal homogeneity

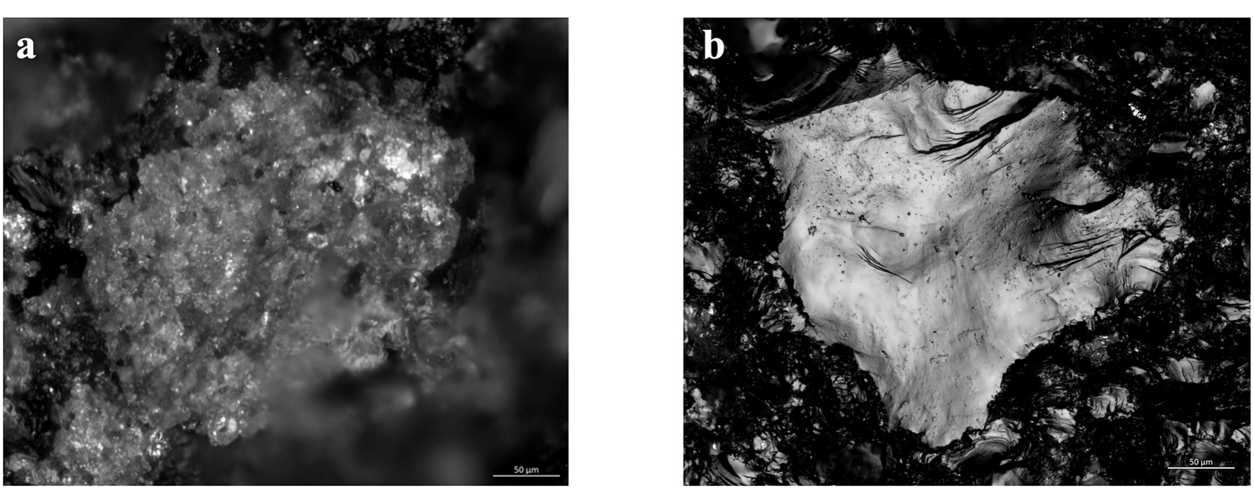

Fig. 7. Quartz crystals described on the quartzite samples before use. a. Type 1. characterized by a prominent surface and irregular microtopography, x20 optical objective; b. Type 2. characterized by a flat surface, less reflection and clear visibility, x20 optical objective.

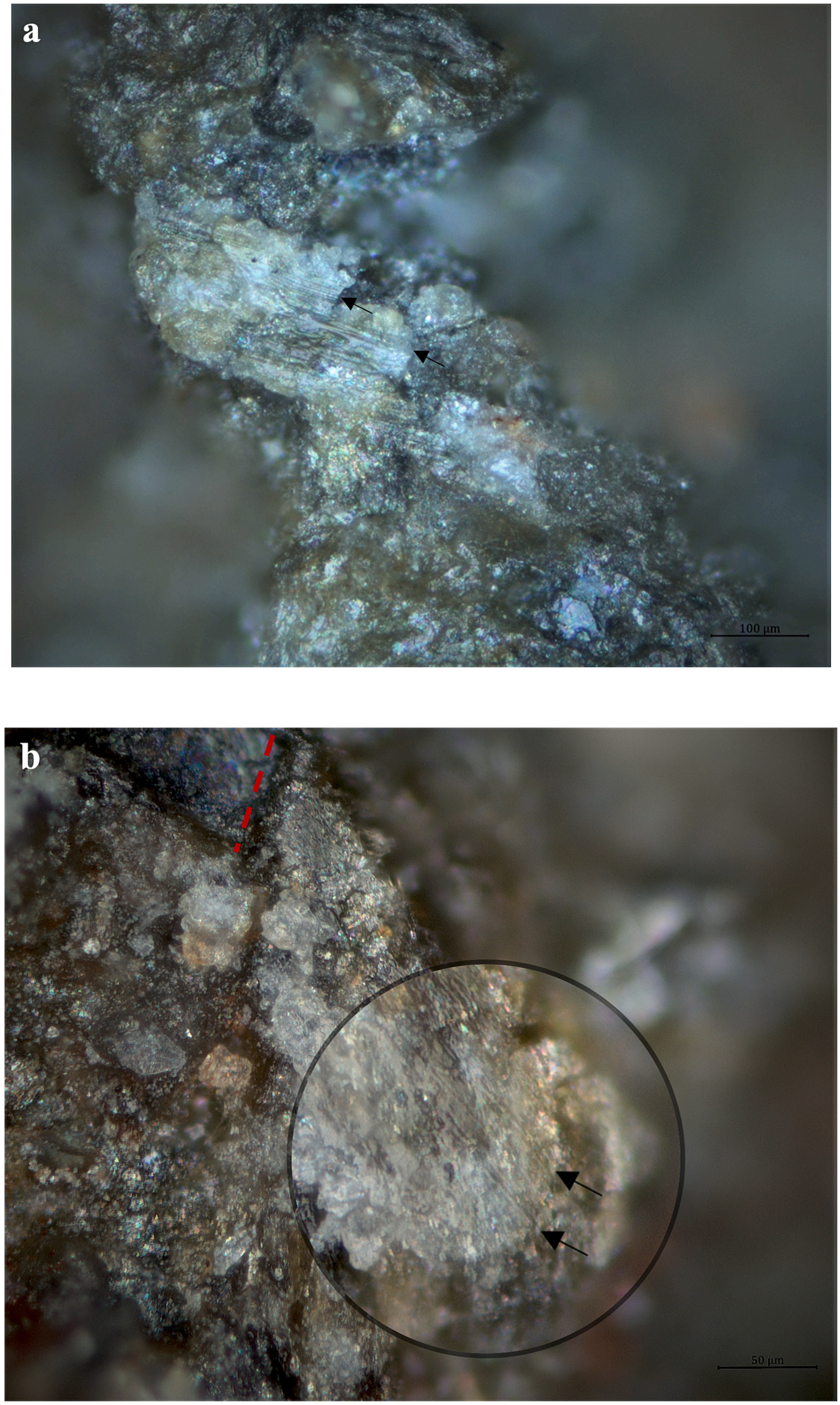

Fig. 8. Use-wear due to *Cedrus Atlantica* wood processing for 60 min; a. Irregular crystal (Type 1) with a high degree of flatness, plastically deformed with formation of long sleeks (black arrows); x10 optical objective. b. Long sleeks (black arrows) and rounded blunt edge (discontinuous red line) formed on Type 1 crystal after removal of the left part of the crystal and the relative flatness of the right one, x20 optical objective.

degree and the presence or absence of technological cracks on their surface.

Generally, more visible use-wear were detected on Type 2 crystals, after the hard materials processing. Moreover, several use-wear traces described after an interval of use disappeared during the succeeding one, due to repeated damage, after each use (Fig. 9). The processing of soft materials, meat and fresh hide, did not show any clear modifications on both crystal's types under the digital or optical microscope.

- **Macro-scars on the tool's edge**

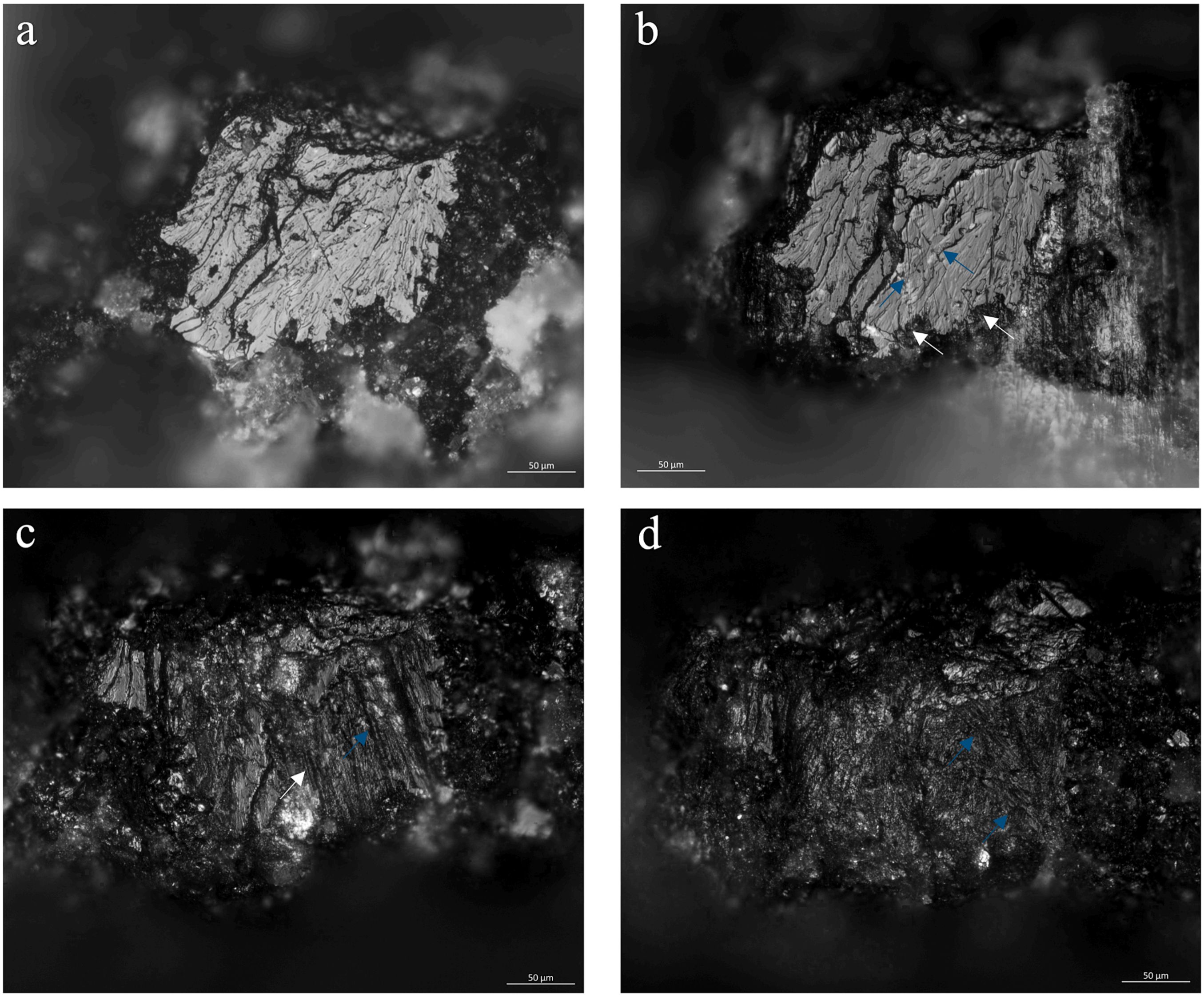

Fig. 9. Sequential experiment on quartzite due to dry wood scraping (x200). a. before use. the crystal shows technological micro-scars and large furrows with different shapes and directions; b. after 5 min, the formation of long sleeks (blue arrows) and the removal of small particles from the crystal's side parallel to the edge axis (white arrows); c. After 15 min, the removal of a large surface of the crystal and occurrence of sleeks (white arrows) and furrows (blue arrows) perpendicular to the edge axis; d. after 60 min, the disappearance of all use-wear except some unclear and few furrows.

The friction with the worked material leads to edge macro and micro fractures, and micro-flakes removal, ultimately damaging the edge and resulting in use-wear formation such as edge bluntness and macro-scars. It is argued that in lithic raw materials, although most studies have been focusing on flint artefacts, criteria such as location, shape, and distribution, could be beneficial for the motion and the worked material hardness determination (e.g., Tringham, 1974; Odell and Odell-Vereecken, 1980; Prost, 1990). In this work, macro-scars on experimental samples were observed mainly on the flakes used to process the hard materials. However, the correlation between diagnostic macro-scar type and motion or hardness of the worked materials has not been observed. In our experiments, different forms and shapes of macro-scars were detected on the same edge after each use cycle. This has been confirmed by the typological variability observed within the removed micro-flakes' shape and size (Fig. 6). Edge bluntness was detected both at the macroscopic and microscopic scale on the flakes used for bone and wood processing (Fig. 8).

- **Micro-scars on the crystal ridges**

Previous works have highlighted the importance of micro-scars in determining the tool's kinematic; during mechanical friction, micro-scars are formed on the crystal's sides located in the opposite direction to the applied motion (Clemente Conte et al., 2015; Clemente Conte and Gibaja, 2009; Gibaja et al., 2009; Knutsson, 1988a). The microscopic analysis of the experimental flakes revealed the same process. However, several technological micro-scars were detected directly after the flakes knapping on different sides of the crystals. The micro-scars due to use were detected mainly on the flakes used for hard materials resulting from the crystals' sides fragmentation or the extension of the technological ones (Fig. 9). The difference between the technological and use-wear micro-scars seems to be hard to identify in some cases. However, those micro-scars related to use are mainly concentrated on the edge and in several cases associated with striations (Knutsson, 1988a).

- **Striations**

On different raw materials, striations can be used to reconstruct the kinematics of movements based on their direction in comparison to the tool's edge axis (Semenov, 1964; Keeley, 1980; Plisson, 1985; Mansur-Franchomme, 1986). Using the upright microscope, several technological linear marks were observed before use (Fig. 9). This could be potentially explained by the frictional interaction between the core and the knapped flake when the latter is being removed. This fracturing process likely results in the material removal from the crystal's surface and sides. During and after the experiments, striations resulting from the use, have been mainly recorded after wood and bone processing, including sleeks and furrows. Some of them were identified in association with the micro-scars on the crystal's ridge as a starting point (Fig. 11a). The sleeks were detected since the first phase of use (5 min), and throughout different use intervals, characterized by their abundance and distribution on the same flat grains (Type 2). The formation of furrows was observed progressively after successive uses.

- **Micro-polish**

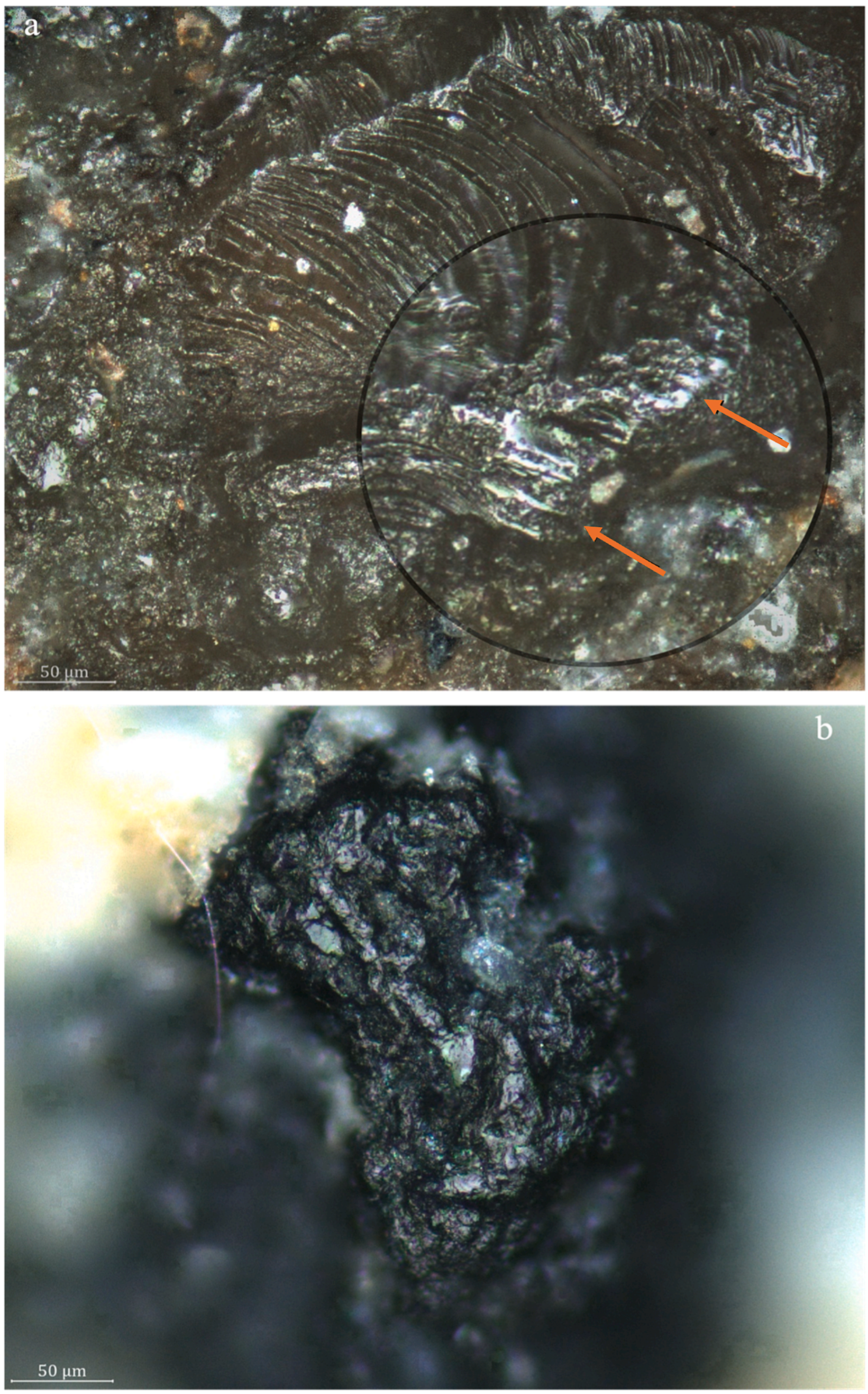

Fig. 10. Micro-polishes resulting from bone processing for 60 min. a. Smooth medium flat micro-polish with parallel direction to the edge axis, close mesh, high density and clear irregular contour due to dry bone sawing, x20 optical objective; b. Smooth micro-polish developed on a high micro-surface characterized by a medium flat micro-topography due to fresh bone scraping, x20 optical objective.

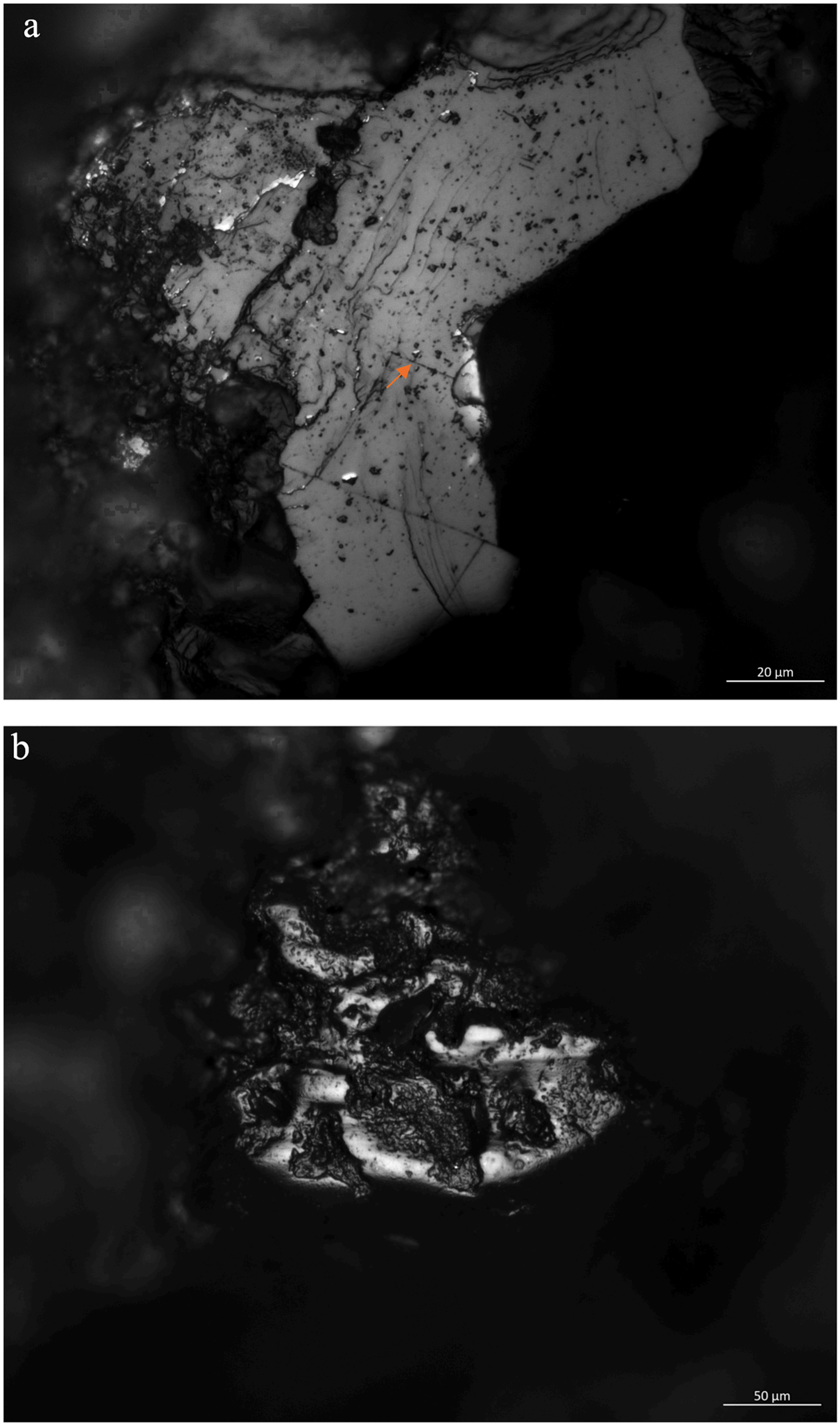

Fig. 11. Micro-polish resulting from wood processing for 30–60 min. a. smooth flat micro-polish with a compact mesh, high density, and clear regular contour, associated with mechanical abrasion (pits), micro-scars and furrows (orange arrow), x50 optical objective. b. smooth domed micro-polish with an intermediate mesh, and hard undulated microtopography due to fresh wood scraping, x20 optical objective.

Micro-polish is poorly documented and described on coarse-grained materials (Pedergnana and Ollé, 2017), a challenge attributed to its limited visibility and formation primarily on the highest surface of the micro-topography (Clemente Conte and Gibaja, 2009; Pedergnana and Ollé, 2017; Stemp et al., 2013). In this study, micro-polish was observed on flakes used for processing bone and wood in different states.

Dry bone sawing produced a micro-polish with a smooth texture, close mesh, clear irregular contour, high density, and its micro-topography seems to be medium flat. The polish direction strongly indicates a parallel motion relative to the edge axis (Fig. 10a).

Scraping fresh bone, on the other hand, created a micro-polish with slightly rougher texture compared to the dry bone polish. This polish predominantly formed on the highest parts of the micro-topography and displayed a close mesh, high density, and hard moderately flat micro-topography (Fig. 10b). Although the direction of the micro-polish was unclear due to the limited surface area on which it is formed, its vertical extension from the edge toward the surface gave indication about the applied transversal motion

In both cases, bone micro-polish was observed only after prolonged tool use, ranging from 30 to 60 min.

Wood processing yielded multiple micro-polishes depending on the task's duration and the state of the worked material (fresh or dry). Scraping dry wood resulted, after 15 min, in a temporary micro-polish with a rough texture and flat micro-topography. This polish shared similarities with the generic weak micro-polish or micro-poli indifférencié, previously described on flint (Vaughan, 1985; Mansur-Franchomme, 1986). However, it disappeared during the succeeding use of the tool, due to material loss.

Sawing dry wood produced a smooth, flat micro-polish with a compact mesh, high density, and a clear regular contour. This polish developed on the crystal's ridge, perpendicular to the edge axis, and was associated with micro-scars and furrows (Fig. 11a).

Scraping fresh wood produced a micro-polished micro-surface with a limited distribution. However, it displays a distinct abrasive property, similar to the one known on flint (Plisson, 1985; Vaughan, 1985, Mansur-Franchomme, 1986). This micro-polish is characterized by a smooth domed texture, an intermediate mesh, and a hard undulated micro-topography (Fig. 11b).

- **Crystals' mechanical abrasion**

In quartzite samples, the crystal's mechanical abrasion, as previously stated, is an alteration that impacts the surface of the quartz crystal, potentially leading to the formation of pits on its micro-surface or a partial or complete disappearance of the original crystal. We detected both types during hard materials (bone and wood) processing. The pits were detected on several crystals with flat micro-surface characterized by varied shapes and forms (Fig. 11a). On the other hand, the aggressive continuous abrasion was predominantly observed on crystals with technological furrows and cracks. In Fig. 9, we recorded sequentially this abrasion on a flat crystal (Type 2) subjected to dry wood scraping. The result, after 5 min of use, indicates the occurrence of long sleeks perpendicular to the edge axis, along with micro-scars on the adjacent parallel edge, formed due to the mechanical gradual pecking (abrasion). Following 15 min of scraping, a large surface of the original crystal was removed and long striations with different depths (sleeks and furrows) were formed. After 60 min, the entire crystal's surface and previously recorded striations disappeared, and only indistinct furrows were detected oriented perpendicular to the edge axis.

5.2. Archaeological artefacts

From the selected 40 archaeological artefacts, 12 have been excluded because of the absence of any indications of use (macro or microscopic traces), 16 showed insufficient or post-depositional traces such as a single generic weak polish (Vaughan, 1985), isolated striations or multiple ones displaying random directions. Twelve tools demonstrated clear evidence of use, including the presence of different types of use-wear traces (see Table 3 for all details on each sample).

Blunt edge was macroscopically identified and documented on two archaeological artefacts: an end-scraper (Tool N°424), and a flake (Tool N°505). The end-scraper, used for bone processing, exhibited a flat bluntness associated with two polished micro-surfaces at microscopic scale. On the other hand, the flake displayed a rounded bluntness macroscopically associated with bevelled bluntness, detected under the microscope on the parallel ridge of several crystals, and associated with long sleeks, resulting from transversal motion (Fig. 12).

The striations are the most prevalent use-wear trace identified on the studied archaeological tools. Consistent with the experimental results, striations were found either grouped on the same crystal or on different ones distributed across the same surface, all oriented in the same direction. Both sleeks and furrows were detected, showing different directions indicating the kinematics (SD2_Fig. 2a, 4a, 5a).

Furthermore, it was observed that striations are present in conjunction with micro-scars (SD2_Fig. 5a), blunt edge (SD2_Fig. 2a, 3c) and/or mechanical abrasion (SD2_Fig. 4a, 6c) in the same micro-surface of the edge and some cases on the same crystaĺs surface. This has also been observed in our experimental samples.

Micro-polish was identified and described on 6 lithics, including different characteristics. We detected well-extended polished micro-surfaces with clear features matching those on the experimental samples, as well as less developed surfaces.

Wood micro-polish was identified on the convergent scraper (Tool N°418), developed on the perpendicular ridge of the crystal. It is characterized by a smooth texture, clear regular contour, a high-density compact mesh, and a flat micro-topography (SD2_Fig. 7c). These features align with the polished micro-surface described on the experimental sample QTZ-W5, which was used for sawing dry *Nerium oleander* wood (Fig. 13).

Microscopic examination on the crystals along the same edge showed additional use-wear, including rounded edge bluntness, pits and multiples striations with a parallel direction to the edge axis (SD 2_Fig. 7).

On the other hand, two polished micro-surfaces resulting from bone processing were identified on the active edge of one end-scraper (Tool N°424), associated with a macroscopic flat bluntness of the edge. Both polishes exhibited a smooth texture, high density, closed mesh and medium flat to domed micro-topography. These same characteristics were observed on the experimental sample QTZ-B2, which was used to saw a dry *Bos taurus* rib (Fig. 13).

On the remaining four archaeological samples, the detected micro-polishes were developed on very narrow micro-surfaces and did not exhibit any clear characteristics matching those described on the experimental tools (SD_2_Fig. 2b, 2c,4d). Therefore, their presence, along with associated use-wear, was considered as additional evidence of the tool use, rather than identifying the worked material.

The mechanical abrasion was observed on 8 archaeological samples, mainly affecting the crystals with flat surface (Type 2). Both gradual abrasion, and pits were identified on multiple crystals near the active edge, mainly associated with the bluntness of the crystal's ridges, striations or both features.

However, the combination of the mechanical abrasion with the other use-wear patterns revealed

that the tools with evidence of longitudinal motion displayed only the presence of pits on the crystal's surface (SD_2Fig. 2a, 7a). In contrast, the tools used for transversal motions showed a combination of pits and gradual abrasion on the crystal's ridges, oriented parallel to the edge axis (SD_2Fig. 4c, 6b, 6c).

Generally, among the 12 lithic samples examined, our results provide evidence of both bone (n = 1) and wood (n = 1) processing. Additionally, 7 samples showed use-wear associated with transversal motion, 2 samples with longitudinal motion, and 2 samples with evidence of double motions (transversal and longitudinal). Only one sample (N°733)

Table 3
Results of the use-wear study on the Aterian lithics from Rhafas cave.

Tool's N°	Typology	Raw material	Layer	Square	Detected use-wear	Motion(s) and worked material
1077	Side scraper	quartzite	3a	E7	Striations, micro-scars, mechanical abrasion	Transversal & longitudinal task
424	End scraper	quartzite	3b	G11	Edge bluntness, micro-polish	Bone scraping
410	Point	quartzite	3b	G11	Striations, edge bluntness, mechnical abrasion, micro-polish	Longitudinal task
505	Flake	quartzite	3a	*H*10	Striations, edge bluntness, mechanical abrasion	Transversal task
311	Side scraper	quartzite	3b	E11	Striations, micro-scars, mechanical abrasion	Transversal task
420	Composite tool	quartzite	3a	*H*10	Striations, mechanical abrasion, micro-scars, micro-polish	Transversal task
496	Denticulate	quartzite	3a	G11	Striations, micro-scars	Transversal & longitudinal task
733	Notched flake	quartzite	3a	E7	Edge damage, macro-scars, micro-polish	Used for unknow worked material
1002	Backed Knife	quartzite	3b	F11	Striations, micro-scars, micro-polish	Transversal task
330	Side scraper	quartzite	3a	G11	Edge blutness, mechanical abrasion, striations	Transversal task
418	Convergent scraper	quartzite	3a	E7	Micro-scars, mechanical abrasion, striations, blunt edge, micro-polish	Longitudinal task on woody material
212	Flake	quartzite	3a	*H*10	Striation, mechanical abrasion, micro-scars	Longitudinal task

displayed use-wear e.g., micro-polish and macro-scars, indicating the tool use. However, no definite evidence regarding the type of motion or the material processed were identified on this artefact (Table 3).

6. Discussion

The study of stone tools technology and use is crucial for better understanding the origins of major behavioural shifts. One of the key moments in the evolution of human behaviour is the onset of *Homo sapiens* populations in the African continent (Grün et al., 1996; Stringer, 2016; Hublin et al., 2017; Richter et al., 2017; Scerri et al., 2018; McBrearty and Brooks, 2000; Vidal et al., 2022). From the archaeological record in North Africa, the emergence of *Homo sapiens* and the complex behaviour is associated with the occurrence of a new cultural and technological repertoire during the Middle Stone Age, including pigment and shell beads, interpreted as elements for symbolic expression (Vanhaeren et al., 2006; Bouzouggar et al., 2007a; d'Errico et al., 2009; El Hajraoui et al., 2012; Sehasseh et al., 2021), bone and ivory tools (El Hajraoui, 1994; El Hajraoui et al., 2012; Bouzouggar et al., 2018; Hallet et al., 2021), and macro-botanical and marine remains, indicating dietary diversity (Campmas et al., 2016; Marquer et al., 2022).

Regarding the lithic industries, the Aterian industry is marked by the adoption of new technological choices and tool design, such as the production of blades, bladelets, bifacial foliates and pedunculated tools (Bouzouggar et al., 2012; Debénath and El Hajraoui, 2012; Dibble et al., 2013; Spinapolice and Garcea, 2014). Such technological novelties are also associated with the use of different raw materials, both fine and coarse-grained rocks, which is likely to reflect the importance of both types of rocks in the Aterian techno-economy (Wengler, 1993a; Bouzouggar, 1997a; Debénath and El Hajraoui, 2012; Longet, 2023). Therefore, the use-wear analysis of Aterian lithic assemblages, including the coarse-grained rocks, is important to fully understand the demands and implications of the new technological choices.

In our study, we addressed this question by focusing on the use-wear analysis, combined with a dedicated experimental reference collection, of the quartzite assemblage of Rhafas cave. The experimental replications included in this work have allowed us to (1) understand the performance of quartzite during the processing of different materials, (2) create a use-wear reference collection, and (3) use the latter to the study and interpretation of the use-wear traces identified on the archaeological artefacts. Our results allowed us to access the dynamic performance of quartzite after being subjected to mechanical stress, which, recorded in three main stages, can be summarized as follows: the first contact with the worked material, mainly the hard ones, leads to the edge scarring, during which the protruding micro-flakes are removed. This step also shows the formation of the first micro use-wear on quartz crystals such as the sleeks and micro-scars. The second stage demonstrates a stronger brittle behaviour (Knutsson, 1988a), characterized by an eventual increase in the micro-flakes number and size, and thus, the possible loss of most previous use-wear. This is followed by a progressive edge stabilization, leading to new use-wear formation including the abrasive ones (e.g., micro-polish), that marks the third stage.

Previous studies have discussed this behaviour and attributed it to the alternative dominance between brittle fracture and plastic deformation during coarse-grained rock use (Knutsson, 1988a; Ollé and Vergès, 2008; 2014; Ollé et al., 2016; Pedergnana and Ollé, 2017; Pedergnana et al., 2017) which may result in a continuous use-wear formation and removal (Ollé and Vergès, 2008). Although the general behaviour remains the same, the brittle fracture's degree differs depending on the applied motion, which influences the edge performance. Indeed, the transversal motions resulted in a lower brittle fracture and higher edge performance, contrary to the longitudinal ones, which show a lower performance since the first minutes of use. This is due to multiple factors that, in some cases, are interrelated. For instance, in dry wood sawing, the edge could be efficient during the first five minutes, while being in contact with the outer bark and the vascular cambium, despite the edge scarring. The contact with the sapwood, however, reflects a high resistance of the latter leading to a strong brittle fracture. In addition to that, the edge gets stuck in the grooves formed by the sawing motion, resulting in additional removed micro-flakes due to the minimum contact angle change, and thus a progressive edge dulling.

Different use-wear traces described in the experiment and on the archaeological samples reflect indications about the applied motions, the worked material, or both. In contrast, the processing of soft materials did not produce any clearly defined use-wear. This underrepresentation could be related to the long duration of use required for the microscopic wear to develop, and the low hardness degree of the worked material, which result in reduced pressure and friction with the tool's edge, and thus limited or unclear use-wear.

The absence of use-wear related to soft material processing (e.g., meat, fresh hide) on the archaeological samples are likely to be explained by their weak formation, and the challenge of identifying them under the optical microscope, rather than the absence of the worked material at the site.

The most abundant use-wear are micro-scars and striations developed mainly on the type 2 crystals. Their association with the same crystals throughout the edge or on a limited area gives a higher certainty about the applied motion. Additionally, unlike flint on which the process of a given worked material produces homogeneous striations with similar characteristics (Keeley, 1980; Vaughan, 1985; Mansur-Franchomme, 1986), the use of quartzite flakes to work wood and bone resulted in both sleeks and furrows on the same edge, and the same crystals in some cases. This may be explained by several factors that could lead to their formation such as the worked material, the removed micro-flakes, and perhaps exterior factors such as abrasive dust (Mansur-Franchomme, 1986).

The micro-polish, as mentioned above, poses a challenge when it

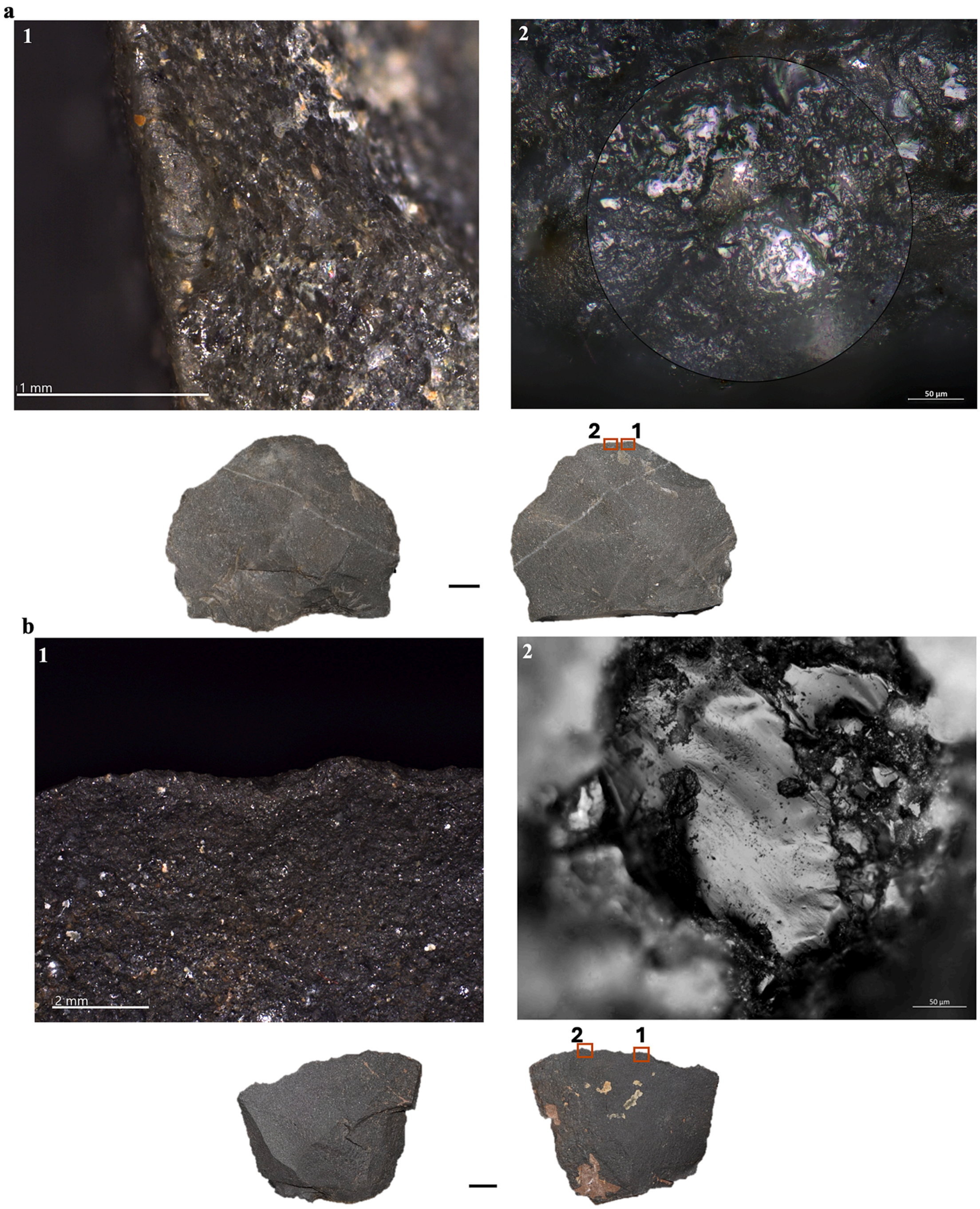

Fig. 12. A. end scraper (n°424) used for bone processing. 1_flat blunt edge, x5 optical objective; 2_smooth domed polished micro-surfaces, x20 optical objective. b. flake (n°505) used for a transversal task. 1_rounded blunt edge, x5 optical objective; 2_bevelled blunt edge and long superficial sleeks on quartz crystal's surface (type 2).

comes to quartzite raw material, due to the uneven micro-topography and its formation on limited micro-surface. It has been reported that it is less frequent and has a slow formation on coarse-grained rocks compared to flint (Clemente Conte and Gibaja, 2009; Knutsson et al., 2015). In addition, previous works have distinguished micro-polish with smooth and rough textures using SEM (Pedergnana and Ollé, 2017). Results of our sequential experiments showed that micro-polish with clear characteristics occurred only after a long duration of hard materials processing (between 30 and 60 min). When observed under the optical microscope, the micro-polish exhibited different extension degrees, influenced by the applied motion in several instances. Notably, the transversal tasks produced a more pronounced extension than the longitudinal ones due to the lower contact angle ($30^\circ < x < 45^\circ$), and thus a larger contacted surface.

The description of micro-polishes on each sample revealed both similar and different characteristics, which may be related to factors such as the nature of the worked material, its state, the applied motion, and the angle of attack.

Our experiments on both dry wood and bone produced micro-polishes with a smooth texture and high density. However, while dry wood polish exhibits a clear regular contour, a compact mesh and a flat micro-topography, the dry bone polish is characterized by an irregular contour, close mesh and a moderately flat micro-topography. These similarities and differences were also observed on the archaeological

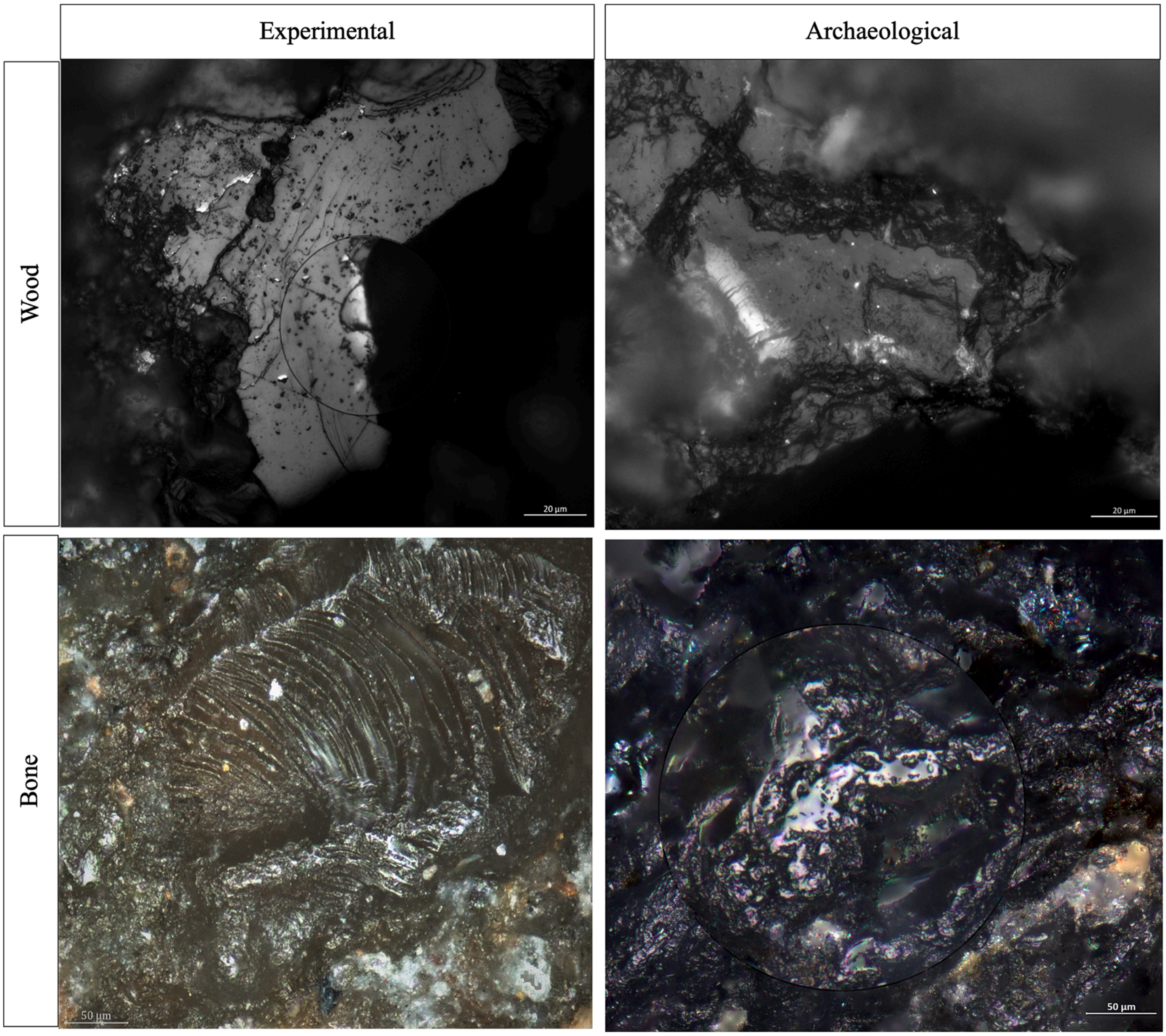

Fig. 13. Micro-polishes on experimental quartzite (QTZ-W5 for wood, 30 min; QTZ-B2 for bone, 60 min), and archaeological tools showing similar micro-polishes, used for wood (418) and bone (424).

samples (Fig. 13b and 13d).

Furthermore, both dry bone and fresh wood have yielded micro-polishes with a similar texture and micro-topography typical to the ones on flint (Keeley, 1980; Plisson, 1985; Vaughan, 1985; Mansur-Franchomme, 1986). This resemblance between quartzite and flint micro-polishes has been previously noted by Plisson (1985) regarding fresh bone (p. 54), and wood (p. 66), and more recently on other coarse-grained rock (Aleo, 2023).

The study of the archaeological tools, supported by the above-mentioned experimental data, has yielded significant results, despite the small sample size. Most evidence indicates the use of Rhafas tools for a long duration including the tools' dimensions, the retouch, and the presence of well-developed micro-polishes known by their slow formation on this type of rock. In addition, the transversal motion seems to be the most dominant, which is compatible with the experimental results showing the feasibility and the high performance of such movement compared to the longitudinal one. The determination of bone and wood micro-polishes suggests that both materials were processed in situ, or outside and the used lithics were brought to the cave.

The bone micro-polishes described on the end-scraper (N°424), and associated with flat blunt edge suggests that, based on experiments, may have resulted from a scraping task related to bone tools manufacturing. Although no bone artefact has been found at Rhafas cave yet, the bone raw material is very abundant at the site (Wengler, 1993a), and this technology is already well-known and documented from other Aterian contexts (El Hajraoui and Debénath, 2012; Bouzouggar et al., 2018; Hallet et al., 2021). The wood micro-polish, on the other hand, may be related to activities such as gathering wood for fuel or the manufacture of wooden objects (Bencomo Viala et al., 2020).

In general, the results of the use-wear analysis on the selected artefacts from the MSA sequence of Rhafas cave have allowed us to identify the function of the quartzite artefacts during the Aterian occupations at the site. The determination of the site's function as well as the comparison with the climatic and the paleoenvironmental data, however, require an enlargement of the sample size, thus enlarging the reference collection.

Future works should focus on the development of experiments dedicated to other worked materials identified in the MSA archaeological record in North Africa (e.g., pigment, marine shells, fish, plants, and hunting activities). This will enhance our understanding of the performance and uses of coarse-grained materials during the Aterian. Moreover, comparing use-wear results between coarse-grained and flinty tools will be crucial for comprehending the significance of each raw material within the Aterian techno-economy at Rhafas cave. This approach will facilitate comparative analysis with previous and ongoing use-wear studies on Aterian sequences as e.g., Ifri n'Ammar and Bizmoune (Tomasso, 2021; Djellal et al, unpublished results).

From the methodological perspective, the combination of different microscopes and magnifications is needed to better record different modifications and use-wear on these types of rocks, as previously recommended by several authors (Borel et al., 2014; Knutsson et al., 2015; Ollé et al., 2016).

The result obtained here showed the possibility of the optical microscope for the worked material determination when the tool is used for a prolonged duration and the micro-polish is well developed. However, the presence of non-recognized use-wear on some Rhafas samples, and the absence of clear ones on the experimental lithics used for soft materials require the extension of the reference collection and the employment of a complementary approach that includes SEM and LSCM for the analysis of the crystals at very high magnifications and the micro-polish quantification.

7. Conclusion

This work represents the first use-wear analysis on coarse-grained materials from the northern African Aterian context. Quartzite artefacts from the Aterian layers (3a and 3b) at Rhafas cave have been studied following a dedicated experimental protocol including raw material procurement, experiments, and the use-wear analysis. The results of our experiments have shown the dynamic response and suitability of quartzite raw material to mechanical friction, and how that led to the continuous appearance and disappearance of use-wear at each interval of different materials processing. This means that the detected use-wear on the archaeological samples could represent the last use, or they could have persisted from previous ones depending on several factors such as the nature of the worked material, its hardness degree, the applied motions and the intentional or unintentional change of the contact angle.

The monitoring of the formation processes associated with different use-wear has allowed for a better understanding of the differences between use-wear types and consequently create the first reference collection of use-wear on quartzite raw material from the region. Most described use-wear during experiments provided indications about the worked materials' hardness degree, the applied motion and/or the worked material. Notably, the similarities between micro-polishes on quartzite from dry bone and fresh wood, when compared with those known on flint, highlight the need for future studies to compare use-wear across different raw materials. However, the employment of different observation techniques and microscopes is required for this perspective.

The use of the reference collection for the study of the Aterian samples from Rhafas cave has revealed the first direct evidence of coarse-grained quartzite tools during the Aterian to process materials such as bone and wood. This result, in addition to the technological variability of the quartzite tools, highlights the importance of this raw material within the Aterian technological toolkit at Rhafas cave. Moreover, the wide range of lithic raw materials, including quartzite, likely reflects the high mobility of these human groups, their extensive procurement territories, and possibly large exchange networks between human groups (Wengler, 1993a; Bouzouggar et al., 2007a; Longet, 2023).

The results of this study offer new perspectives for understanding the properties of quartzite, the function of tools, and the behavior of Aterian human groups. To gain further insights into the Aterian lithics variability and their relationship to stone tool functions, our upcoming investigation will expand the reference collection by incorporating additional worked materials and employing different microscopes (SEM and LSCM) for a complementary approach.

CRediT authorship contribution statement

Youssef Djellal: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Abdeljalil Bouzouggar:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **El Hassan Talbi:** Writing – review & editing, Methodology, Investigation. **Benoit Longet:** Writing – review & editing, Investigation. **Noufel Ghayati:** Writing – review & editing, Investigation. **Antonella Pedergnana:** Writing – review & editing, Methodology. **João Marreiros:** Writing – review & editing, Methodology, Investigation.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105146.

Data availability

Data will be made available on request.

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