



Exploring Basalt: A Methodological Framework for Analysing Wear Traces on Basalt Tools

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Abstract

Basalt is a widely used raw material for tool manufacture at prehistoric sites, but a unified methodology for assessing how hominins used basalt in prehistory is lacking. A comprehensive experimental investigation of basalt tools is, thus, necessary to establish a reliable methodological framework that can be used to explore the functional properties of archaeological basalt assemblages.

The aim of this study is to contribute to the development of a methodological framework for the analysis of use-wear on basalt tools. Basalt, characterised by its distinct mechanical and structural properties and unique response to mechanical stress, requires specialised treatment and investigation.

To address this, our basalt varieties were characterised using SEM–EDS analysis. Sequential experiments were conducted, using the experimental basalt tools in different activities, including butchery, hide, bone and woodworking to determine use-wear formation patterns. Subsequently, various analytical tools, including optical and scanning electron microscopes, were used to analyse macro- and micro-wear traces on basalt.

Our results provide useful information on methodological aspects of use-wear formation on basalt. The inclusion of detailed cleaning and experimental protocols enhanced the robustness of our methodology. Furthermore, the combined utilisation of various microscopes enabled to compile a comprehensive and complementary information on such a complex raw material such as basalt and to characterise thoroughly the diagnostic features of the micro-wear traces (*e.g.* edge damage, rounding, polish).

Keywords Basalt · Micro-wear analysis · Methodological approach · Experiments · Multi-technique analysis

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Introduction

The field of micro-wear analysis on prehistoric lithic artefacts has experienced a substantial transformation over the past six decades. This evolution can be attributed not only to advancements in modern technology and the development of more sophisticated analytical techniques but also to notable progress in methodological approaches.

Traditionally, the majority of micro-wear studies were focused on chert or flint (*e.g.* Tringham et al., 1974; Odell, 1977; Keeley, 1980; Vaughan, 1985; Grace, 1989; González and Ibañez, 1994; Levi-Sala, 1996), leading to the most extensive development of micro-wear methodology for this raw material. The “preference” for flint can be attributed to several factors, with the abundance of this raw material in numerous archaeological sites and the conspicuous ease of observing wear patterns using optical light microscopes on flint or chert materials standing out as primary reasons. This does not imply a lack of effort or investigations into non-flint raw materials. In fact, numerous researchers (*e.g.* Kamminga, 1978; Greiser & Sheets, 1979; Foix & Bradley, 1985; Knutsson, 1988; Knutsson et al., 1988; Richards, 1988; Sussman, 1988; Hurcombe, 1992; Pereira, 1996) made significant contributions by establishing essential methodological frameworks for the examination of micro-wear on non-flint raw materials. However, most of these researchers recognised the difficulties of analysing “coarser” raw materials given the analytical challenges imposed by the physical and mechanical properties of these raw materials.

Along with the progress of new analytical tools and equipment and driven by the pervasive occurrence of non-flint raw materials at numerous prehistoric sites, there has been a growing interest in recent years in developing further the micro-wear studies on non-flint raw materials such as quartz, quartzite, rock crystal, and various types of lava (Aleo, 2023; Bello-Alonso et al., 2019, 2020; Clemente Conte et al., 2015; Fernández-Marchena & Ollé, 2016; Lemorini et al., 2014; Ollé et al., 2016; Peder gnana & Ollé, 2017; Peder gnana et al., 2016a, 2020; Taipale & Rots, 2019). Notably, the adoption of novel analytical techniques and methods (*e.g.* differential interference contrast (DIC) in optical microscopes, scanning electron microscopy (SEM), 3D digital and confocal microscopes), as proposed in some of these studies, has substantially enhanced the ability to overcome the analytical limitations imposed by the unique physical properties of these rocks.

Different lavas in general, and basalt in particular, have attracted the attention of researchers in the field of micro-wear studies almost since the beginning of the discipline (Price-Beggerly, 1976; Wyant and Bayham, 1976; Stafford, 1977; Kamminga, 1978; Montgomery, 1978; Odell, 1980; Foix and Bradley, 1985; Richards, 1988). These early works established a comprehensive methodological framework for micro-wear analysis on basalt, accompanied by a diverse experimental programme covering a wide range of activities and some basalt varieties.

Subsequently, researchers have continued to contribute to the field by developing experimental programmes involving different types of lava, such as andesite, dolerite, basalt, rhyolite, and obsidian (Hurcombe, 1992; McDevitt, 1994;

Rodríguez Rodríguez, 1997, 2009; Clemente Conte and Gibaja, 2009; Asryan et al., 2014; Clemente Conte et al., 2015; Bello-Alonso et al., 2019, 2020; Aleo, 2023).

Nevertheless, despite the considerable interest and research dedicated to advancing micro-wear studies on basalt and other types of lava, there are several crucial aspects that remain unexplored or insufficiently investigated. (1) One of these aspects, as underscored also by Richards (1988) and still relevant today, is the significant variability within basalt. This variability encompasses diverse mineral sizes (coarse to fine), nature (tough to more fragile), and textures (rough to glassy) influencing on the type of wear patterns that develop on tools made of different basalts. Such a variable nature of basalt demands careful consideration and control of numerous factors within the raw material itself during experimentation. Consequently, making close comparisons between various experimental basalt tools utilised in identical activities and under the same conditions frequently proves to be a challenging task. (2) The experimental reference collections for basalt lag behind those of more common materials like flint or obsidian. To address this, it is crucial to construct an experimental reference collection that will serve, firstly, to gain insights into the behaviour of basalt under varied experimental conditions and wear development when working with diverse materials; secondly, to establish a reliable reference collection for interpreting archaeological assemblages; and finally, to evolve continuously, incorporating new basalt varieties, experimental activities, and contact materials. (3) Studying basalt at the microscopic level presents inherent challenges owing to the diverse characteristics of the raw material. Despite recent advancements, optical microscopes remain the predominant choice in micro-wear studies of basalt (*e.g.* Clemente Conte et al., 2015; Bello-Alonso et al., 2019, 2020; Aleo, 2023). While optical microscopes are undeniably valuable in micro-wear studies, the variable mineral size, high reflectivity of these minerals under the optical microscope, and the diverse surface topography collectively pose difficulties in observing and identifying use-wear traces on basalt. These limitations can be addressed using more advanced microscopy techniques such as scanning electron microscopy (SEM). SEM has been sporadically employed for analysing micro-wear traces on basalt (Richards, 1988). However, during that period, the SEM equipment faced notable limitations, such as restricted stage dimensions, limited working distance, and the obligatory need for coating. Consequently, only small segments of the tool's used edge could undergo analysis, necessitating the cutting off portions from the used edge, rendering the tool irreversibly damaged for analysis and precluding a complete reconstruction. Moreover, the mandatory coating of samples involved the application of special products, mainly acidic solutions, for coating removal, which proved impractical for certain rocks like basalt due to their elemental composition. More recently, Asryan et al. (2014) tested modern and advanced environmental scanning electron microscopy on basalt, demonstrating its utility in high-quality micro-wear studies without damaging the tool. However, there is a notable gap in systematic studies that apply both optical and scanning electronic microscopes to various types of basalt and that could contribute significantly to correctly identifying and interpreting different micro-wear traces on this rock. (4) Methodology applied to clean experimental and archaeological basalt tools is frequently overlooked and

insufficiently explained aspect, despite its crucial role. It demands meticulous attention due to the distinctive chemical properties of basalt that can be adversely affected by inappropriate cleaning procedures. To ensure the preservation of valuable archaeological and experimental artefacts and the accuracy of subsequent micro-wear analysis, it is essential to follow a methodical approach for cleaning these tools.

Given the prevalence and significance of basalt lithic assemblages at numerous prehistoric sites, coupled with acknowledged gaps in the study of micro-wear on basalt, and considering the existing research in the field of micro-wear studies on various lavas, including basalt, this study aims to further develop the methodological framework for investigating micro-wear on basalt flake tools. This involves constructing and developing an experimental reference collection comprising diverse basalt varieties and involving various activities and contact materials. Additionally, the study aims to highlight the importance of characterising use-wear features for each basalt variety and tracking their development across various experimental stages. It seeks also to systematically apply optical and scanning electron microscopes in micro-wear studies of basalt, providing insights into their efficacy in characterising distinct micro-wear traces on basalt surfaces. Finally, the study aims to introduce meticulous cleaning protocols for both experimental and archaeological basalt tools, facilitating the cleaning of samples without causing macro- and micro-damage.

Materials and Methods

Experimental Reference Collection

Many authors have emphasised the importance of building up an experimental reference collection to facilitate the creation of modern comparatives and the execution of activities that likely occurred in the past using experimental stone tools (Semenov, 1964; Tringham et al., 1974, Keeley & Newcomer, 1977; Hayden, 1979, Anderson, 1980; Keeley, 1980; Beyries, 1982; Kamminga, 1982; Plisson, 1985; Vaughan, 1985; van Gijn, 1990; Ollé, 2003; Rots, 2010; Kononenko, 2011; Pedernana et al., 2014; Fernández-Marchena & Ollé, 2016; Xhufclair et al., 2016; Martín-Viveros et al., 2020). Considering the big variability of basalt and its limited representation in experimental reference collections, and recognising that firsthand experimentation is essential for comprehending wear formation patterns, it was of utmost importance for us to develop a thorough micro-wear experimental collection specifically for this raw material. We started our study with four basalt varieties originating from different continents as our experiments are thought to serve as a reference for testing the results on key archaeological sites across different Pleistocene periods. Specifically, we aim to test our results on the Lower Pleistocene site of Olduvai Bed 2 FC East and West in Tanzania (de la Torre & Wehr, 2018), the Middle Pleistocene sites of Mieso in Ethiopia (Benito-Calvo et al., 2014) and Abri du Maras in France (Moncel et al., 2014), and the Upper Pleistocene site of Bagratashen 1 in Armenia (Egeland et al., 2016) in the subsequent phases of our research. Therefore, our experimental programme includes basalt varieties sourced

from the vicinity of these archaeological sites. The experimental programme is currently ongoing, which means that the experimental reference collection will continue to expand with additional experimental activities, worked materials, and a wider range of basalt varieties.

Experimental flakes were knapped from four basalt cobbles originating from the aforementioned regions, specifically basalt 1 from Ethiopia, basalt 2 from Tanzania, basalt 3 from Armenia, and basalt 4 from France. A comprehensive petrographic analysis of these basalt samples and a research paper discussing their intra-raw material variability and its impact on micro-wear formation are currently in progress. As for the general characteristics of these basalt samples, they predominantly exhibit a dark green to grey coloration. Notably, only one of the samples (namely basalt 3 in Fig. 1, originating from Armenia) displays a characteristic fine-grained or aphanitic texture, composed of microscopic crystals not discernible to the naked eye. In all other cases, our basalt samples feature a porphyritic texture, wherein larger crystals of minerals like olivine or plagioclase are embedded in a fine-grained matrix. These samples are generally rich in magnesium (Mg), aluminium (Al), and iron (Fe), with a significant presence of silica (SiO₂). We expect that the petrographic analysis will offer more precise insights into the sample variability we have (Fig. 1 and SupT1).

Skilled experimenter Ch. Lepers at TraceoLab (University of Liège) used direct percussion with hard quartzite hammers to create experimental flakes resembling those found in archaeological sites. Each tool was individually labelled, documented in a database, photographed, and examined for potential damage prior to the experiment. They were then stored in individual zip-lock bags and only taken out just before each experiment.

Moulds and casts of the tool edges were made before use to record their original appearance (Ollé & Vergès, 2014). Moulds were prepared using silicon-based dental impression material (*Provil novo Light*®) by mixing the base paste and catalyst in equal parts. Casts were then made using a bicomponent rigid polyurethane resin (*Feropor PR55*®) by mixing parts A and B in equal parts too. The use of moulds and casts in this study served two purposes. Firstly, creating high-definition casts of the fresh edge is important because once the piece is used, the original fresh edge gets modified, and the cast is the only way to preserve a record of the fresh edge. Additionally, interesting modifications or surface changes can occur during the experiment in areas of the edge that were not documented beforehand. Therefore, the presence of casts provides the only reliable reference for the original state of the edge, enabling accurate comparisons before and after use. Secondly, we aimed to evaluate the effectiveness of moulds and casts for basalt. While moulds and casts are known to be quite efficient with flint and other fine-grained rocks, we wanted to test if they provided sufficient quality and resolution for analysis and whether they perform well with “coarser” basalt varieties. In this study, we used moulds and casts solely to reproduce an exact replica of the unused edge of the tools, ensuring a reference to the original condition.

We initially faced significant challenges with moulding and casting basalt, particularly the “coarser” varieties, as our moulds and casts frequently contained numerous air pockets or air bubbles. These air pockets were often visible in the moulds themselves, resulting probably from improper mixing, incorrect proportions

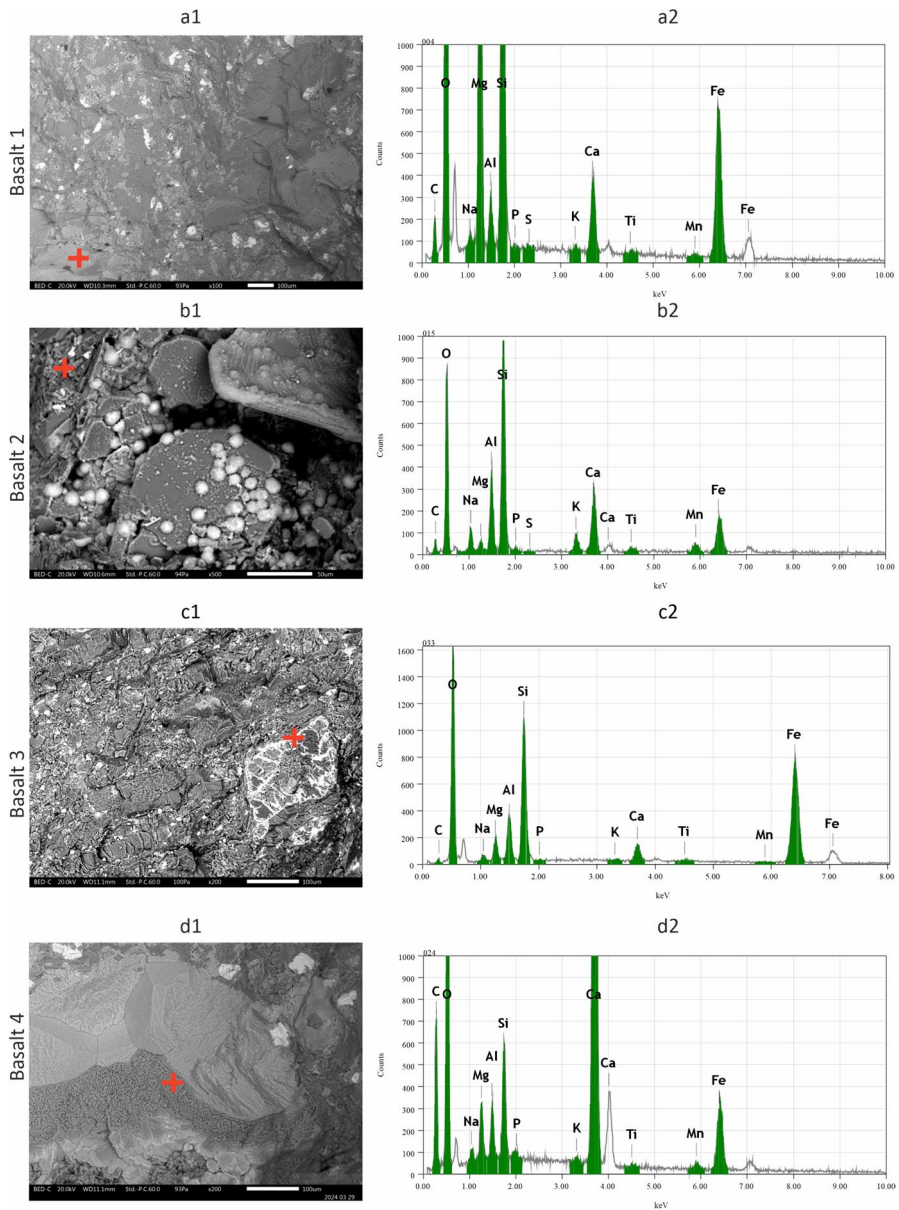


Fig. 1 Elemental characterisation of basalt varieties used in this study, namely basalt 1 from Ethiopia, basalt 2 from Tanzania, basalt 3 from Armenia, and basalt 4 from France: On the left side, SEM micrographs (**a1** to **d1**) showcase distinct basalt types, while their corresponding elemental spectra (**a2** to **d2**) on the right depict the elemental composition, with the analysed points highlighted by a red cross

of moulding materials (base and catalyst), incomplete filling of the tool edge by the moulding material, or variations in temperature or humidity in the laboratory. These issues, compounded by errors in mixing the casting material or incorrect filling of the moulds, led to gaps in the casts and subsequent loss of information from the tool edge. After several trials, we succeeded in producing high-quality casts with minimal air pockets and sufficient resolution for detailed photography (Fig. 4 a1, b1, and c1). However, we acknowledge that achieving such high-quality casts with basalt is challenging.

The experimental program started by conducting experiments that sought to replicate common and well-recognised activities in prehistory. These activities encompassed tasks such as butchery, hide-, bone-, and woodworking. In this context, the materials involved, also referred to as “contact material”, “worked material”, or “object material” (Tringham et al., 1974; Kelley, 1980; Odell, 1980), included fresh and dry hide, flesh, fresh and dry bone, muscular tissues, and fresh and dry wood. Animal remains from roe deer (*Capreolus capreolus*), wild boar (*Sus scrofa*), and cow (*Bos taurus*) carcasses were utilised. Woodworking activities involved the use of elm branches (*Ulmus minor*). We used all four varieties of basalt for each of these materials. The experiments were conducted in both laboratory and outdoor settings. While laboratory experiments may lack some authenticity, we made every effort to replicate natural environmental conditions as closely as possible (Fig. 2 and Table 1). All tools were handheld and designated for individual tasks. Longitudinal unidirectional motion was applied for cutting actions in butchery-related activities, while transverse unidirectional motion was employed for scraping actions in hide-, bone-, and woodworking activities.



Fig. 2 The knapping process of experimental tools (a) and some examples of experiments (b–g): b skinning of roe deer; c scraping of a dry elm branch; d scraping dry hide of roe deer; e scraping of fresh hide from a wild boar; f scraping of a dry cow bone; and g scraping of a fresh cow bone

Table 1 Summary of key experimental variables recorded in this study. Note: each experiment was conducted using four different varieties of basalt

Reference N	Edge angle	Contact material	Species	Movement	Action	Working angle	Working time
Exp123-001	40°	Flesh, tendons, bone	<i>Capreolus capreolus/Sus scrofa</i>	Unidirectional	Cutting	80–90°	15 + 15 + 30
Exp123-002	60°	Fresh wood	<i>Ulmus minor</i>	Unidirectional	Scraping	45–50°	15 + 15 + 30
Exp123-003	50°	Dry hide	<i>Capreolus capreolus</i>	Unidirectional	Scraping	60–70°	15 + 15 + 30
Exp123-004	50°	Dry bone	<i>Bos taurus</i>	Unidirectional	Scraping	40–50°	15 + 15 + 30
Exp123-005	60°	Fresh wood	<i>Ulmus minor</i>	Unidirectional	Scraping	50–70°	15 + 15 + 30
Exp123-006	60°	Dry bone	<i>Bos taurus</i>	Unidirectional	Scraping	50–80°	15 + 15 + 30
Exp123-007	50°	Dry hide	<i>Capreolus capreolus</i>	Unidirectional	Scraping	70–80°	15 + 15 + 30
Exp123-008	30°	Flesh, tendons, bone	<i>Capreolus capreolus/Sus scrofa</i>	Unidirectional	Cutting	80–90°	15 + 15 + 30
Exp123-009	60°	Dry hide	<i>Capreolus capreolus</i>	Unidirectional	Scraping	80–90°	15 + 15 + 30
Exp123-010	50–55°	Flesh, tendons, bone	<i>Capreolus capreolus/Sus scrofa</i>	Unidirectional	Cutting	80–90°	15 + 15 + 30
Exp123-011	45°	Fresh wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15 + 30
Exp123-012	40°	Dry bone	<i>Bos taurus</i>	Unidirectional	Scraping	70–80°	15 + 15 + 30
Exp123-013	50°	Fresh bone	<i>Bos taurus</i>	Unidirectional	Scraping	80–90°	15 + 15
Exp123-014	25°	Flesh, tendons, bone	<i>Capreolus capreolus/Sus scrofa</i>	Unidirectional	Cutting	80–90°	15 + 15 + 30
Exp123-015	40°	Dry bone	<i>Bos taurus</i>	Unidirectional	Scraping	60–70°	15 + 15 + 30
Exp123-016	55°	Dry hide	<i>Capreolus capreolus</i>	Unidirectional	Scraping	80–90°	15 + 15 + 30
Exp123-017	45°	Fresh wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15 + 30
Exp123-018	35°	Fresh hide	<i>Sus scrofa</i>	Unidirectional	Scraping	70–80°	15 + 15
Exp123-019	70°	Dry wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15
Exp123-020	45°	Fresh bone	<i>Bos taurus</i>	Unidirectional	Scraping	80–90°	15 + 15
Exp123-021	50°	Fresh hide	<i>Sus scrofa</i>	Unidirectional	Scraping	70–80°	15 + 15 + 30
Exp123-022	70°	Dry wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15
Exp123-023	50°	Fresh bone	<i>Bos taurus</i>	Unidirectional	Scraping	80–90°	15 + 15 + 30
Exp123-024	60°	Dry wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15
Exp123-027	65°	Dry wood	<i>Ulmus minor</i>	Unidirectional	Scraping	70–90°	15 + 15

The experiments conducted were of a sequential nature. The significance of such experiments has been extensively discussed elsewhere (Ollé & Vergès, 2014, and references therein). In summary, the importance of sequential experiments lies in systematically monitoring and recording the development of use-wear traces at various stages of surface modification. It also involves precisely tracking the evolution of micro-relief throughout the entire duration of the performed activity. The established time sequences for this study were set at 15, 30, and 60 min of use for each experimental piece. Following each time sequence, the tools underwent microscopic analysis before being reused, culminating in a total usage time of 60 min. All aspects of the experiments were meticulously documented on prepared forms before, during, and immediately after each tool use episode. These data were subsequently entered into a database. The used part of the tool was indicated on a sketch on the form, along with details of tool prehension and its positioning and motion relative to the contact material during use. The duration of tool use was recorded with a digital stopwatch. Photographs and video recordings were taken during the experiments in progress, utilising a Canon EOS 2000D camera equipped with an EFS 18–55 mm objective, as well as mobile devices for additional photography and video recording.

Cleaning Procedure and Sample Preparation

Cleaning is an integral component of micro-wear studies, as the presence of dirt and modern contaminants on the surface of stone tools can obscure pre-existing wear traces or can potentially lead to misinterpretations (Tringham et al., 1974; Kelley, 1980). Special attention was given to the cleaning procedure of our experimental basalt tools for several reasons. Firstly, the chemical composition of basalt, including a significant presence of calcium in plagioclase minerals, required a specialised cleaning protocol. Secondly, the cleaning method for basalt tools has not been comprehensively explained in the available literature (*e.g.* Richards, 1988; Clemente Conte et al., 2015). Lastly, one of our goals was to test and assess a cleaning method that would be applicable also to the archaeological basalt artefacts.

The cleaning procedure applied in this study was based on a multi-step approach previously tested in other context and on other rock types (Byrne et al., 2006; Vergès and Ollé, 2011; Ollé and Vergès, 2014). However, adjustments were made to accommodate the unique characteristics of basalt. Notably, basalt contains a significant calcium component in its composition, making the use of hydrochloric acid solutions (HCl) strictly contraindicated, regardless of their strength. Extensive testing revealed that even though no visible macroscopic reactions to HCl were apparent, this solution was capable of inducing structural damage to the basalt through underlying chemical process (Fig. 3). As seen in Fig. 3c, the Ca+ links initially present on the mineral surface disappears or significantly diminishes after being in the HCl solution for 5 min. Conversely, elements previously obscured by the Ca+ links (*e.g.* Mg, Si) exhibit enhanced signals after the layer's removal due to the reaction between calcic plagioclase of basalt with acid.

Considering the potential challenges associated with these “aggressive” cleaning methods and their impact on basalt, the following cleaning method has

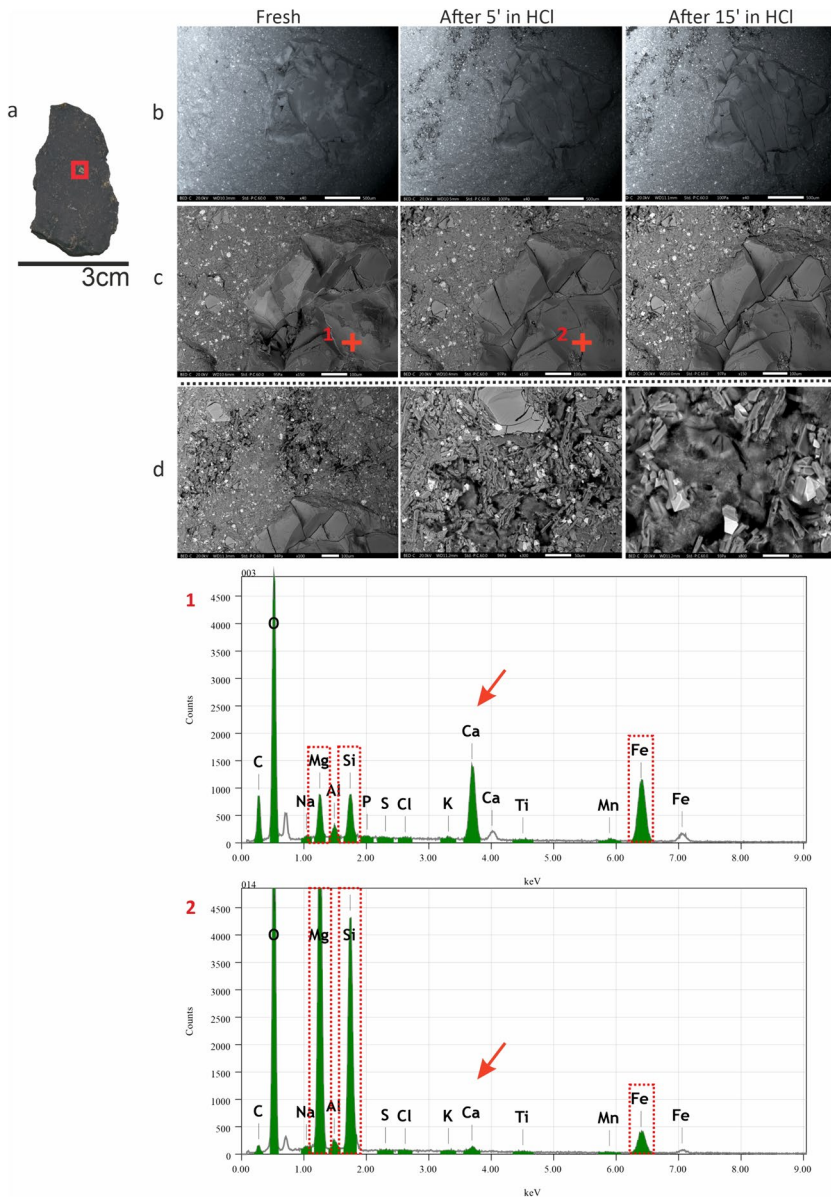


Fig. 3 Impact of a 5% HCl solution on experimental basalt (the basalt variety used is namely basalt 4 from France): **a** Macro image of the experimental basalt featuring a highlighted control area within the red rectangle; **b** controlled area observed under the SEM backscattered electron detector, showcasing the basalt sample at the fresh stage (left), after 5 min (middle), and 15 min (right) of immersion in the HCl solution, revealing evident chemical reactions and micro-structural damage on both the mineral and the surrounding matrix. Original magnification: $\times 40$, scale bar: 500 μm ; **c** close-up of the mineral, highlighting a control point analysed at the fresh stage (1) and after subjecting the sample to the HCl solution for 5 min (2), accompanied by their respective elemental spectra. Arrowhead and dotted lines in spectra 1 and 2 serve as indicators highlighting variations in the quantities of chemical elements (e.g. Ca, Si, Mg, Fe). Original magnification: $\times 150$, scale bar: 100 μm . **d** Detail of structural damage (original magnification: $\times 100$, $\times 300$, and $\times 800$; scale bar: 100 μm , 50 μm , and 20 μm , respectively). The damage is attributed to the reaction between calcic plagioclase and the HCl solution

proven most suitable for cleaning basalt tools in our testing: an initial 20- to 30-min ultrasonic bath using a neutral phosphate-free detergent to remove any particles adhered to the surface, followed by a 10-s rinse with running tap water. The final step involves a 5- to 10-min ultrasonic bath using pure acetone to eliminate any greasy residues resulting from handling. It is important to note that this protocol may not always yield optimal results from the outset, and for certain basalt varieties with a strong roughness linked to large crystallite that can trap residues, a repetition of the cleaning procedure is often necessary, including an additional 10-min bath in pure ethanol and acetone. Hydrogen peroxide (H_2O_2) often employed for the removal of organic residues from flint tools (Ollé & Vergès, 2014; Pedergrana et al., 2016b; 2017, Martín-Viveros & Ollé, 2020) was also tested on our experimental basalt tools. We found that 3% solution of H_2O_2 is quite efficient in removing “difficult” organic residues from basalt surface.

It is also noteworthy that the cleaning protocol demonstrates superior effectiveness when applied to the samples immediately after the experiment, preventing the residues from drying on the tool’s surface. Once these residues have dried and become firmly adhered to the rock’s surface, we observed that their removal becomes considerably more challenging.

Another aspect of cleaning that interested us was the removal of possible residues left after moulding the edge of experimental tools. Upon removing the silicone mould, we observed that particularly the “coarser” varieties of basal had trapped some silicone stains. Additionally, the entire edge of the tool exhibited a greasy film or shadow resulting from the silicone. Immediately after removing the mould from the edge, a 5- to 10-min ultrasonic bath of the experimental tools in pure acetone eliminated some of the silicon residues, but not all, and the “greasy shadow” remained. Therefore, we applied the complete cleaning protocol established for our basalt samples: a 20- to 30-min ultrasonic bath with a neutral, phosphate-free detergent, followed by a 10-s rinse with running tap water, and finally, a 5- to 10-min ultrasonic bath using pure acetone or ethanol. After this process, the silicone stains were almost entirely removed at both macro and microscopic levels, but the “greasy shadow”, though reduced, was still partially present. However, since our experiments were sequential and the cleaning procedure had to be repeated after each sequence, by the end of the third sequence all residues, including the “greasy shadow”, were completely eliminated. Upon microscopic examination of the edges and the areas where the moulds were applied, it is noteworthy that neither the silicon residues nor the “greasy shadow” resulting from moulding material chemically alter the surface of basalt.

To prevent the deposition of modern contaminants, the entire cleaning procedure and subsequent analysis were conducted using powder-free nitrile gloves. Furthermore, following each ultrasonic bath, all tools were dried with compressed air to eliminate any “last-minute” contaminants originating from laboratory surroundings, closures, or airborne sources, and also to avoid the formation of liquid spots that could potentially lead to confusion during microscopic observation.

Microscopic Analysis

This study employed a combined approach utilising optical microscopy (OM) and scanning electron microscopy (SEM) for the microscopic examination of experimental basalt tools.

In the case of optical microscopes, a motorised stereo zoom microscope, the Zeiss Axio Zoom V16, equipped with PlanApo Z objective lenses ($0.5\times/0.125$ and $1.0\times/0.25$) and offering a magnification range spanning from $5.6\times$ to $180\times$ was used. This allowed for imaging of the entire edges of the experimental tools both before and after experimentation, as well as precise localisation of areas of interest. For higher magnifications, the Zeiss Axio Imager M2m metallographic microscope was employed, featuring $10\times$ oculars and six objective lenses (EC Epiplan $5\times/0.13$ HD; EC Epiplan-Neofluar $10\times/0.25$ HD DIC; LD EC Epiplan-Neofluar $20\times/0.22$ DIC; LD Epiplan $20\times/0.40$; LD Epiplan $50\times/0.50$; and LD EC Epiplan-Neofluar $100\times/0.75$ DIC) with magnification capabilities ranging from $50\times$ to $1000\times$. For micro-wear analysis the brightfield contrasting technique was mostly used, although differential interference contrast (DIC) and polarized filter were often employed too to gain additional insights into wear patterns, raw material, and residue characteristics. Image acquisition for both optical microscopes was facilitated using a 5MP AxioCam ICc5 digital camera, and multi-focused images were obtained using ZENcore 3.5, AxioVision SE64, and Helicon Focus 8.0 software. To create panoramic or mosaic images featuring the horizontal stitching of OM and SEM micrographs, the Image Composite Editor (ICE) software was employed.

For scanning electron microscopy (SEM), the JEOL JSM-IT300 model was used, featuring IT300 software and a magnification range from $15\times$ to $35,000\times$ (with the study primarily utilising magnifications ranging from $40\times$ to $2000\times$). Notably, all observations were conducted in low vacuum mode (LV), eliminating the need for sample coating with conductive materials such as gold or carbon. The analysis of micro-wear predominantly relied on a large field secondary electron detector (LV-SED; Probe Current 40 pA, Pressure 40 Pa), while the examination of raw materials and residues was conducted using a back-scattered electron detector (BED-C; Probe Current 60 pA, Pressure 60 Pa). In both cases, a voltage of 20 kV was applied. The SEM microanalysis system, employing energy-dispersive x-ray spectroscopy (EDX or EDS), was employed to determine the chemical composition of the raw materials and residues, and the Analysis Station software was used for the EDS analysis.

Results

In general, it can be stated that all our basalt varieties proved to be quite efficient in various cutting and scraping tasks across different materials. However, the “finer” variety of basalt or the one characterized by a typical aphanitic texture (basalt 3) demonstrated higher efficiency in cutting actions compared to the “coarser” ones (basalt 1, basalt 2, and basalt 4). Interestingly, when engaging in scraping actions on materials such as wood, bone, or hide, no significant differences were observed between the various basalt varieties.

When considering the effectiveness of the edges on our experimental basalt tools, it is important to acknowledge that the response of basalt edges can vary depending on the specific basalt variety and the task performed. In general, “finer” varieties of basalt tend to be more efficient but less durable. On the other hand, “coarser” varieties can be less efficient in certain tasks but demonstrate relatively greater durability.

After using the basalt pieces sequentially over three distinct durations (15, 30, and 60 min), it was evident that none of our basalt varieties exhibited well-developed use-wear traces, even after an hour of intensive use in diverse tasks (Fig. 4). Strikingly, dry hide scraping emerged as the sole activity that yielded well-developed rounding and polish across the used edges of our basalt varieties. In all other scenarios and with different worked materials, the observed use-wear was not as advanced as one might anticipate from prolonged tool utilisation. This limited progression of use-wear traces on diverse basalt varieties is likely linked to the continuous breakage or peeling of basalt minerals, particularly those with coarser dimensions, occurring during their use. This continuous process leads to the creation of fresh surfaces along the tool’s edge. Consequently, even as tool use persists, each instance involves a new, fresher surface making contact with the worked material, thereby generating a certain degree of use-wear. This wear tends to diminish with subsequent peeling or edge fracturing.

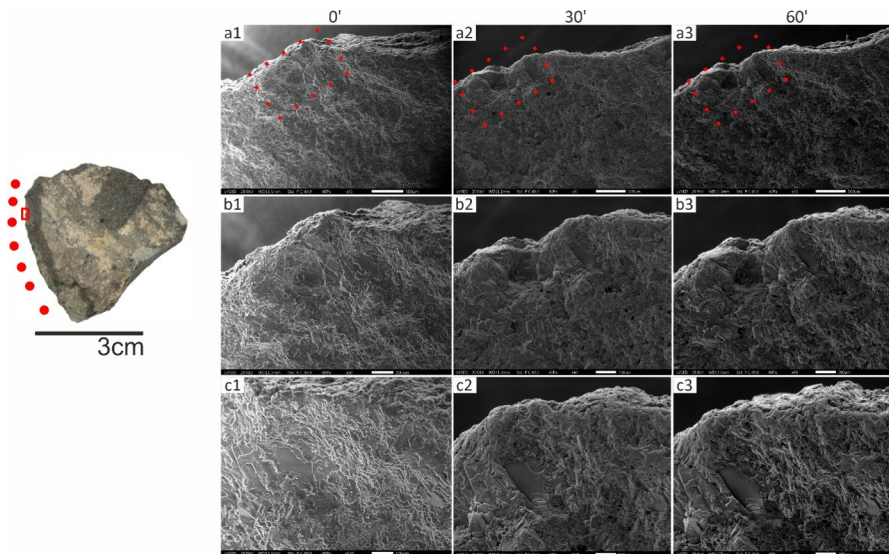


Fig. 4 Basalt tool used sequentially in fresh wood scraping activity (namely basalt 1 variety). The SEM micrographs illustrate the stages of edge transformation: **a1**, **b1**, and **c1** the unused stage of the edge (note: images are captured on the cast of the fresh edge); transformation of the same portion of the edge after 30 min (**a2**, **b2**, and **c2**), where some edge smoothing and small breakages are visible, and 60 min of use (**a3**, **b3**, and **c3**), where the edge becomes slightly more rounded and the small mineral breakages continue. In **a1–a3**: original magnification $\times 35$, scale bar: 500 μm . The dashed rectangle highlights the edge portion and the mineral group undergoing some changes, including small fractures; for **b1–b3**: original magnification $\times 60$, scale bar: 200 μm ; and for **c1–c3**: original magnification $\times 120$, scale bar: 100 μm

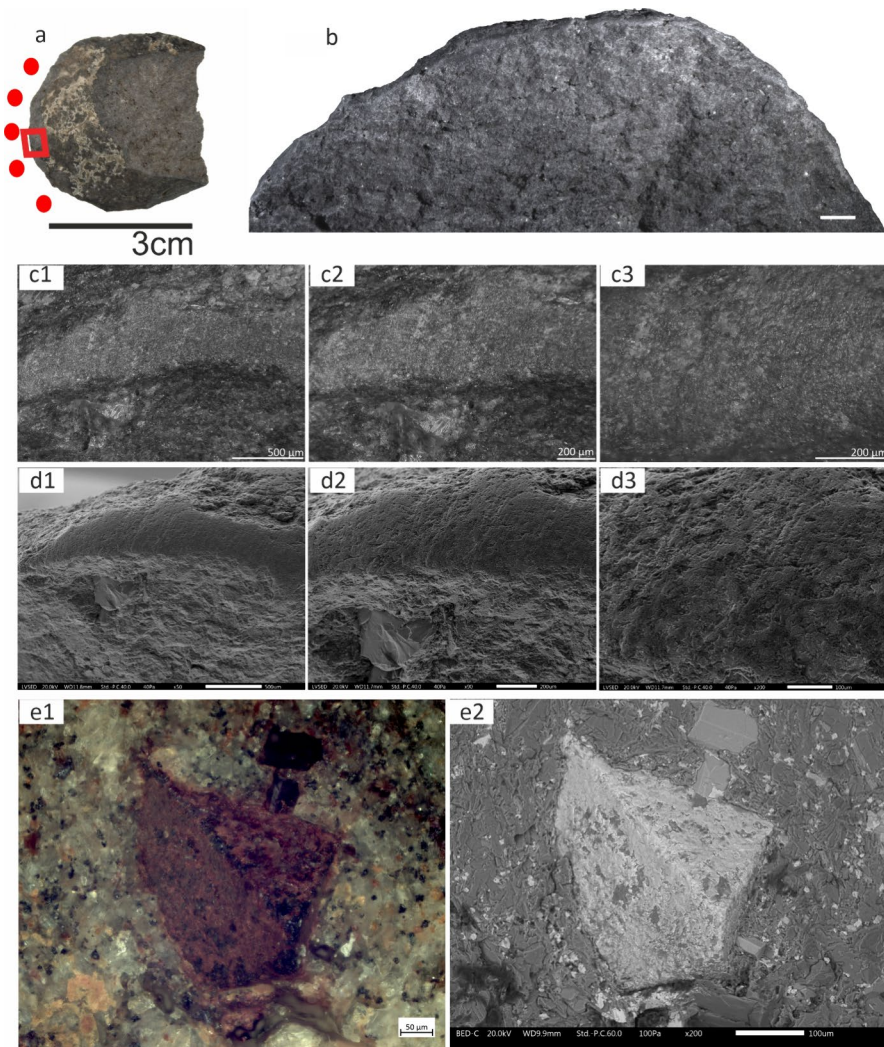


Fig. 5 A basalt tool used in hide-working activity, showing the details of raw material and use-wear through OM and SEM (namely basalt 2 variety). **a** Macroscopic image of the used tool. The used edge is highlighted with dotted line and the area shown in the microscopic images is outlined in a rectangle. **b** Tailed image of the used edge captured by the stereo zoom microscope (original magnification: $\times 11.2$, scale bar: 2000 μm). **c1–c3** The used edge after 60 min of hide-working activity is observed at varying magnifications of metallographic microscope (**c1**: $\times 50$, scale bar: 500 μm ; **c2**: $\times 100$, scale bar: 200 μm ; **c3**: $\times 200$, scale bar: 200 μm). **d1–d3** Detailed view of the same portion of the edge under the SEM secondary electron detector (**d1**: $\times 50$, scale bar: 500 μm ; **d2**: $\times 90$, scale bar: 200 μm ; **d3**: $\times 200$, scale bar: 100 μm). While rounding is visible under both OM and SEM, striations are barely noticeable, even at higher magnifications with OM. In contrast, SEM images clearly show the rounding and polish of the edge and distinctly visualise the linear features or striations. **e1–e2** Microscopic examination of basalt minerals under OM ($\times 200$, scale bar: 50 μm) and SEM backscattered detector ($\times 200$, scale bar: 100 μm)

The application of a multi-analytical approach (OM and SEM) has proven to be remarkably useful in the micro-wear analysis of basalt tools. Both the stereo zoom microscope and metallographic microscope were effective for raw material observation (*e.g.* colour, presence of minerals) and for general characterisation of some of the macro- and micro-wear traces (*e.g.* scars, rounding) (Fig. 5). However, the observation of certain micro-wear features, such as striations and polish, posed challenges when using optical microscopy. These traces, especially striations, were often invisible or unclear under conventional optical magnification. In such cases, the use of SEM not only facilitated the clear visualisation of previously challenging micro-wear traces but also enabled their detailed analysis under higher magnifications.

Edge scarring, striations, rounding, and polish are frequently observed wear traces on the used edges of lithic tools (Semenov, 1964; Tringham et al., 1974, Odell *et al.*, 1976; Keeley, 1980, and others). All these traces have been observed on the basalt tools employed in this study, albeit with varying degrees of development.

Edge Scarring

Some edge scarring was developed on the basalt tools employed for longitudinal motion and cutting action in butchery related activities, particularly with basalt featuring finer minerals. In this case, the scars mostly displayed wide and diffuse initiation, featuring feather, and a few cases, step termination. These primarily adopted a semicircular morphology, with occasional instances of trapezoidal and triangular morphologies. The scars were mostly small (< 1 mm) discreetly distributed on both dorsal and ventral faces. No scars were observed on the edges of tools made from “coarser” basalt varieties, despite their use in analogous motion and activities (Fig. 6).

Only a limited number of scars were developed on the basalt varieties used in wood- and bone-working activities. Once again, it is noteworthy that the basalt with finer minerals exhibited a greater propensity for developing these traces in both activities. During bone-working, the scars typically took on trapezoidal and semi-circular morphologies, featuring wide and diffuse initiation, and feather-, step-, and occasionally hinge-terminations (Fig. 7). Their size ranged between 1 and 2 mm, and their distribution along the utilised edge was isolated, occasionally exhibiting slight overlap. Predominantly, these scars manifested on the leading aspect of the edge, which in both cases was the ventral face. The scant scars arising from wood-working activities were typically isolated, displaying trapezoidal morphologies and step-terminations. In all our experiments, the edge scarring consistently manifests itself during the initial stages of use, typically within the first 15 to 30 min.

Striations

The observation of striations or linear features proved challenging, if not impossible, even at higher magnifications of the optical microscope (*e.g.* $\times 200$, $\times 500$). Following optical microscope observations, we would confidently assert the absence of striations in any of our experimental basalt tools. However, the introduction of the

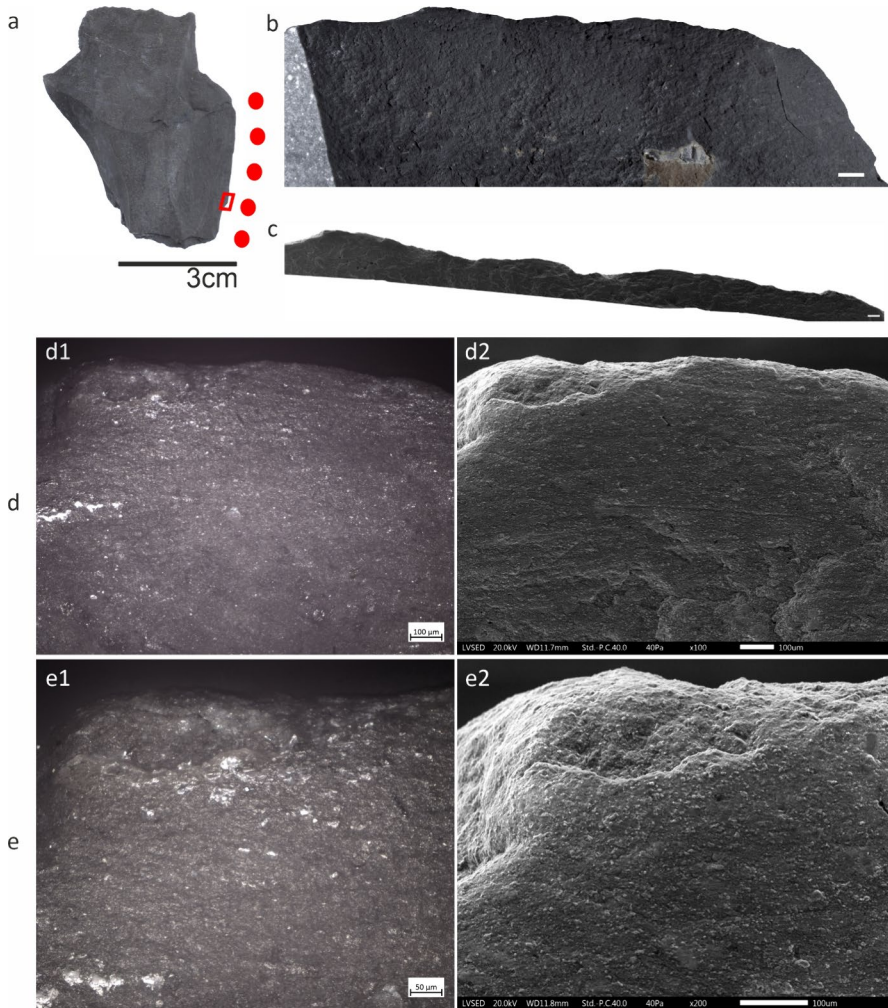


Fig. 6 Use-wear development on a basalt tool after 30 min of butchery activity (namely basalt 3 variety). **a** Macroscopic image of the used tool. The used edge is highlighted with dotted line and the area shown in the microscopic images is outlined in a rectangle. **b** Tailed image of the ventral face of the used edge, captured by a stereo zoom microscope (original magnification: $\times 11.2$, scale bar: 2000 μm). **c** Tailed image of the ventral face of the used edge, as observed through SEM secondary electron detector. Notable micro-scars and linear features are discernible even at relatively low magnification (original magnification: $\times 40$, scale bar: 500 μm). **d** Close-up of edge smoothing, micro-scars, and linear features, captured under OM (d1, original magnification: $\times 100$, scale bar: 100 μm) and SEM (d2, original magnification: $\times 100$, scale bar: 100 μm). Linear features are distinctly visible under SEM, contrasting with the OM view. **e** Detailed examination of the same edge point under OM (e1, original magnification: $\times 200$, scale bar: 50 μm) and SEM (e2, original magnification: $\times 200$, scale bar: 100 μm)

scanning electron microscope (SEM) altered the landscape. The detection of striations became possible only through the application of the SEM, revealing previously unseen details (Fig. 8).

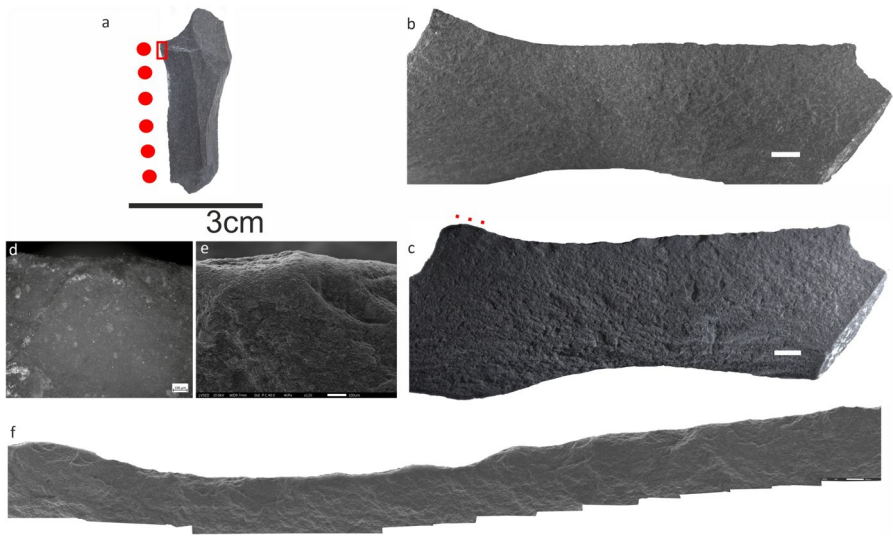


Fig. 7 Use-wear patterns on a basalt tool after 30 min of dry bone scraping activity (namely basalt 3 variety). **a** Macroscopic image of the used tool. The used edge is highlighted with dotted line and the area shown in the microscopic images **d** and **e** is outlined in a rectangle. **b** Tailed image of the ventral face of the unused edge, captured by a stereo zoom microscope (original magnification: $\times 11.2$, scale bar: $2000\ \mu\text{m}$). **c** Tailed image of the same edge after 30 min of use, revealing noticeable edge scarring. **d** and **e** Detail of rounding and edge scarring on a specific point (dash lined on the tailed image “C”) of the used edge under the OM (**d**, original magnification: $\times 100$, scale bar: $100\ \mu\text{m}$) and SEM (**e**, original magnification: $\times 120$, scale bar: $100\ \mu\text{m}$). The SEM micrograph (**e**) provides enhanced visibility of the rounding and scars. **f** Tiled image of the edge under the SEM showing the scar and rounding distribution along the used edge (original magnification: $\times 40$, scale bar $500\ \mu\text{m}$)

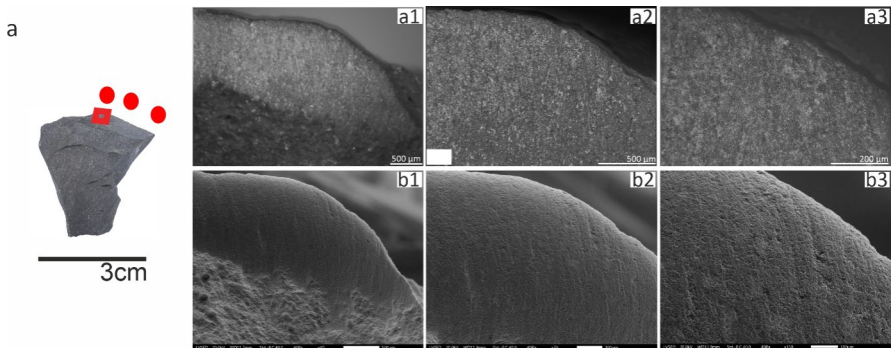


Fig. 8 Basalt tool used in dry hide scraping activity for 60 min (namely basalt 3 variety). The same portion of the edge under the OM and SEM. **a** Macroscopic image of the used tool. The used edge is highlighted with dotted line and the area shown in the microscopic images with a rectangle. **a1–a3** OM images illustrating the edge at different magnifications (**a1**, original magnification: $\times 50$, scale bar: $500\ \mu\text{m}$; **a2**, original magnification: $\times 100$, scale bar: $500\ \mu\text{m}$; and **a3**, original magnification: $\times 200$, scale bar: $200\ \mu\text{m}$). **b1–b3** SEM images using the secondary electron detector, showcasing the same portion of the edge at different magnifications (**b1**, original magnification: $\times 40$, scale bar: $500\ \mu\text{m}$; **b2**, original magnification: $\times 80$, scale bar: $200\ \mu\text{m}$; and **b3**, original magnification: $\times 150$, scale bar: $100\ \mu\text{m}$). Transversally distributed linear features, prominently visible at low magnifications of SEM (**b1**), are almost imperceptible even at higher magnifications of the OM (**a3**)

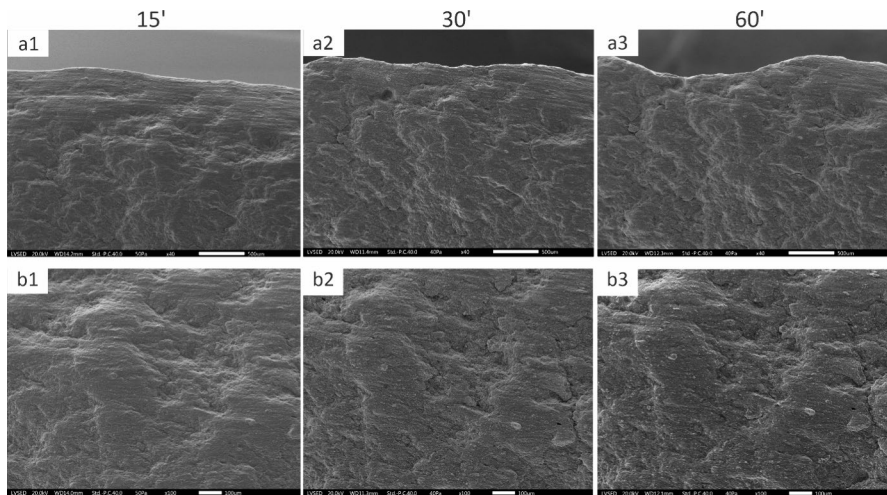


Fig. 9 Development of linear features on a basalt tool (namely basalt 3 variety) used for longitudinal motion and cutting action in a butchery-related activity across three different time-periods (15, 30, and 60 min). **a1–a3** The same edge segment after 15 (**a1**), 30 (**a2**), and 60 (**a3**) min of use. While exhibiting gradual edge wear over time, the linear features, prominently visible after 15 min (**a1**), appear to diminish with prolonged use (**a2** and **a3**). The SEM secondary electron detector images are captured at an original magnification of $\times 40$ with a scale bar of 500 μm . **b1–b3** Detail of the same edge segment at $\times 100$ magnification with a scale bar of 100 μm

Under the SEM, striations became visible along the edges of the “finer” basalt variety, resulting from longitudinal motion (cutting action) during butchery-related activities. These striations predominantly ran parallel but also displayed oblique orientations to the utilised edge, with lengths varying between 20 and 100 μm . Notably, these striations manifested as early as the initial 15 min of use, intensifying during the subsequent 15 to 30 min. Extended use (> 30 min) led to their disappearance or partial concealment, likely due to edge rounding or deformation (Fig. 9). In contrast, when employing “coarser” basalt varieties in a similar manner and for the same activity, no striations were observed. This absence can be attributed to the earlier mentioned breakage or peeling of the minerals in these “coarser” basalt varieties.

Some striations were also identified on the tools employed for transversal motion in dry hide scraping activity. The “finer” basalt exhibited the most pronounced striations (Fig. 8 b1–b3), although some of the “coarser” basalts also displayed these traces (Fig. 5 d1–d3). Their distribution was perpendicular to the used edge and their length varied from 10 to 50 μm . Depending on the mineral size of basalt involved in the process of striation formation, some striations were notably fine and narrow, while others were slightly wider. In this case, the appearance and disappearance of striation on “finer” and “coarser” varieties was quite dynamic. While many striations were formed during the initial 15 to 20 min of use, they tended to diminish around the 30-min mark but reappeared again at the later stage of use, around 40 to 60 min. No striations were detected on the tools used during fresh hide working activities across all basalt varieties.

Only woodworking with “fine” basalt produced some isolated perpendicularly distributed striations on the tool’s edge. No striations were detected on the surfaces of “coarser” basalt varieties, regardless of their involvement in fresh or dry wood-scraping activities. Additionally, no striations were observed on the tools employed in both dry and fresh bone-working activities.

Rounding and Polish

Only dry hide-working led to a notable development of rounding and polish across all our basalt varieties, spanning the entire utilised edge (Fig. 10). Remarkably, rounding and surface smoothing emerged as the predominant attritional processes in this particular activity.

Even within a short period of use (< 15 min), these distinctive traces became evident, and prolonged tool use further intensified their presence (Fig. 11). The resulting polish exhibits a generally rough texture, particularly pronounced in the edge rim and extending into the faces depending on how the tool was used. This observation aligns logically with the high working angle applied during the experiment, ensuring continuous contact between the tool’s rim and the worked material.

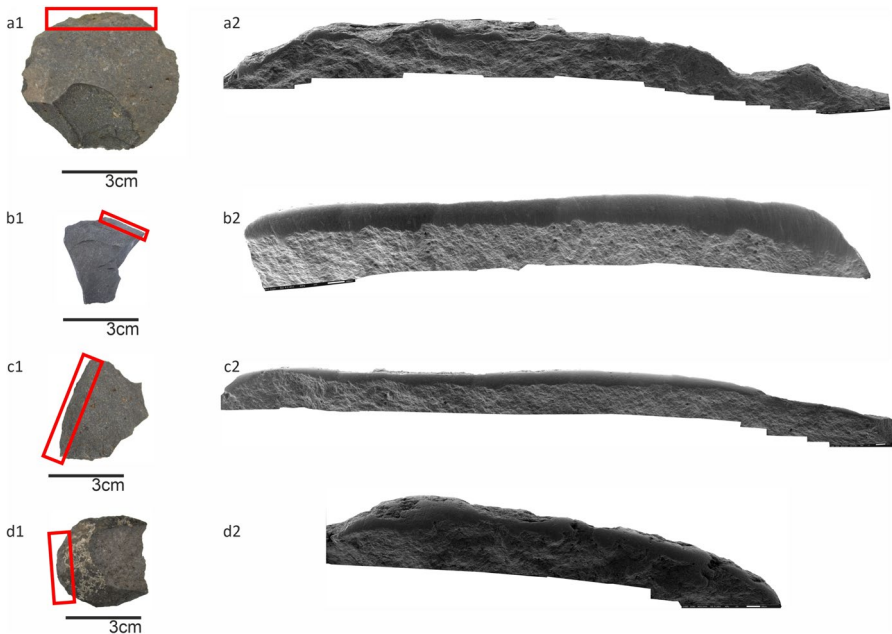


Fig. 10 Basalt tools after 60 min of dry hide scraping activity. **a1** basalt 1 variety, **b1** basalt 3 variety, **c1** basalt 4 variety, and **d1** basalt 2 variety. Macroscopic images of the tools with used edges highlighted by rectangle. **a2**, **b2**, **c2**, and **d2**. Tailed images of the entire used edge derived from SEM secondary electron detector micrographs (original magnification: $\times 35$, scale bar: 500 μm), showing well-developed rounding and polish along the used edge

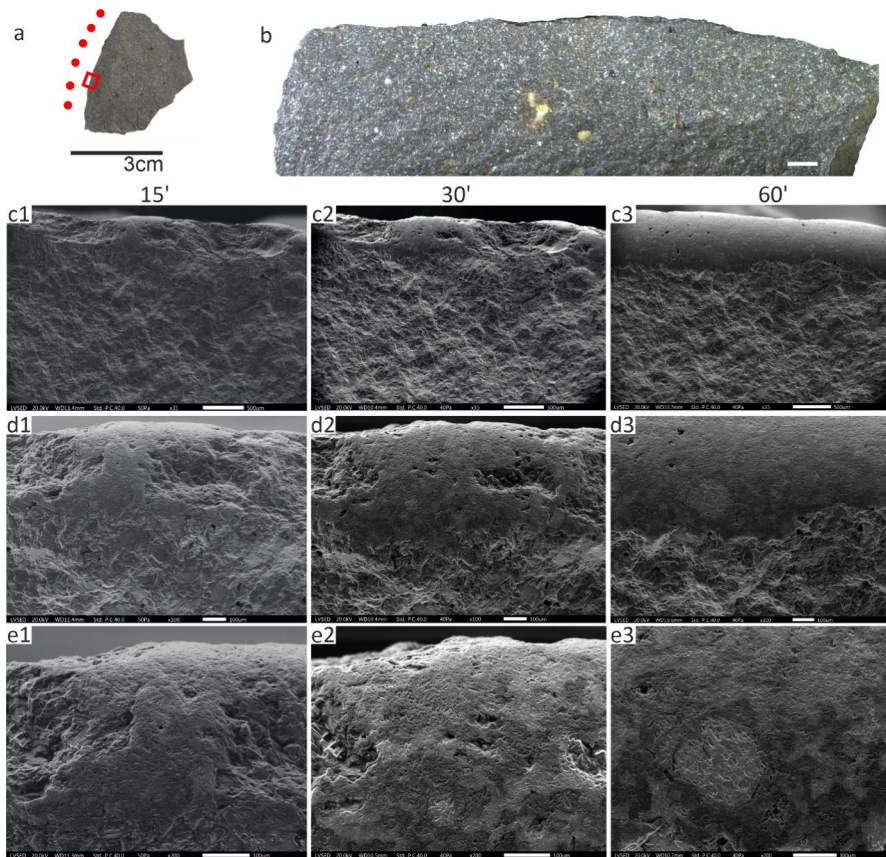


Fig. 11 Edge rounding and polish evolution during dry hide scraping activity (namely basalt 4). **a** Macroscopic illustration of the experimental tool. The used edge is highlighted with a dotted line and the exact point shown in the SEM micrographs—with a rectangle. **b** Tailed image of the tool's fresh edge before experimentation, captured by stereo zoom microscope (original magnification: $\times 11.2$, scale bar: 2000 μm). Sequence of SEM micrographs showcasing the transformation of the same portion of the edge after 15 (**c1**, **d1**, and **e1**), 30 (**c2**, **d2**, and **e2**), and 60 (**c3**, **d3**, and **e3**) min of use (**c1–c3**: original magnification $\times 35$, scale bar: 500 μm ; **d1–d3**: original magnification $\times 100$, scale bar: 100 μm ; **e1–e3**: original magnification $\times 200$, scale bar: 100 μm)

Across all other activities such as butchery, bone-working, and woodworking, edge rounding and polish were almost absent within a short period of use (15 min). It was only after extended use (30 to 60 min) that these traces exhibited slight to moderate development in some parts of the edge (Fig. 12). The “finer” basalt variety tended to display slightly more developed traces, particularly evident in the context of dry bone-working activity. In both “finer” and “coarser” basalt varieties, the polish tended to be predominantly rough-textured and dull. Notably, we attribute the continuous breakage of minerals or peeling as having a significant impact on the further development of these traces.

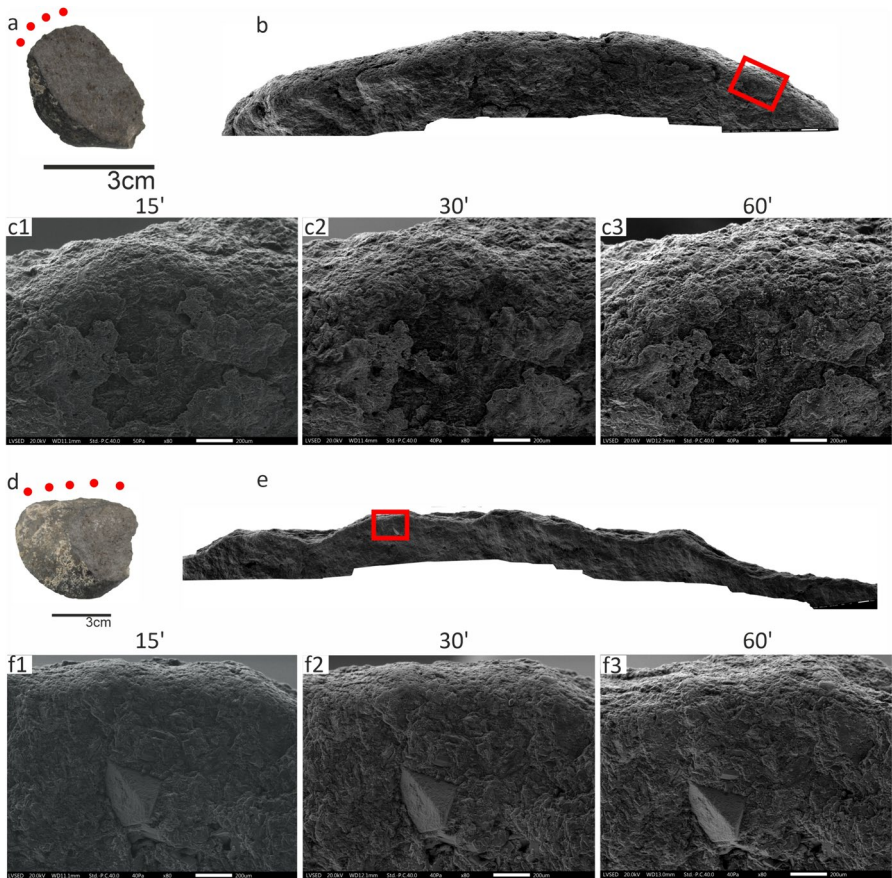


Fig. 12 Use-wear development on “coarser” basalt used sequentially in bone- and woodworking activities. **a** Basalt tool utilised in fresh bone scraping activity (namely basalt 2 variety), emphasising the used edge with a dotted line. **b** Tailed SEM image of the used edge after 60 min of use, showing overall edge smoothing and rounding (original magnification: $\times 35$, scale bar: 500 μm). The rectangle highlights the specific edge area depicted in the SEM micrographs. **c1–c3** Sequence of SEM micrographs illustrating the transformation of the same portion of the edge after 15 (**c1**), 30 (**c2**), and 60 (**c3**) min of use (original magnification $\times 80$, scale bar: 200 μm). **d** Basalt tool used in fresh wood scraping activity (namely basalt 2 variety). **e** Tailed view of the entire edge after 60 min of use (original magnification: $\times 35$, scale bar: 500 μm). **e1–e3** Sequence of SEM micrographs displaying the alteration of the same edge area after 15 (**e1**), 30 (**e2**), and 60 (**e3**) min of use (original magnification $\times 80$, scale bar: 200 μm). Little transformation and mineral breakage or peeling are evident in both cases

Discussion

Our study employed a meticulous approach to investigate the efficiency of basalt tools in different use activities and the characteristics of the use-wear development through a well-designed experimental framework and advanced micro-wear analysis techniques. Building upon the recognised significance of experimental

reference collections in lithic tool studies, we initiated our study with a diverse set of basalt varieties sourced from different continents.

While a comprehensive petrographic study of our basalt varieties is currently underway, it remains challenging at this stage to precisely assess the impact of raw material variability on micro-wear formation across different basalt types. Nevertheless, drawing from our preliminary characterisation of the raw material, we can offer some initial insights. Generally, all our basalt varieties exhibit brittle mechanical behaviour, yet some differences emerge in wear formation patterns. These differences likely arise from the unique mechanical structure and mineral composition inherent to each basalt variety. Specifically, we observed in our experimental studies that the larger the minerals, the more challenging it becomes for wear traces, particularly rounding and polish, to develop.

Basalt varieties with finer minerals show superior efficacy in cutting actions but these are less durable, while basalts with coarser minerals exhibit lower efficiency but greater durability. Micro-wear formation due to scraping actions on materials such as wood, bone, or hide did not exhibit significant differences across any of the basalt varieties. Despite prolonged use, none of the basalt varieties exhibited well-developed use-wear traces, except in dry hide scraping, where rounding and polish were notably present after short use. Our assessment indicates that, especially in the case of basalt featuring coarser minerals, the minimum time necessary for noticeable use-wear development should surpass 30 min, unless the contact material proves highly abrasive, such as dry hide, facilitating the onset of micro-wear within a shorter usage period of 10–15 min.

Traditionally, different characteristics of micro-wear (*e.g.* size, morphology, and distribution of scars; rounding and polish texture and their distribution; type and distribution of striations) have served as crucial indicators for interpreting the type of motion, actions undertaken, activities, and contact materials involved, especially when experimenting with flint (Tringham et al., 1974; Odell, 1977; Keeley, 1980; Vaughan, 1985; Grace, 1989; González and Ibañez, 1994). However, when applied to basalt, our experimental results reveal a certain level of complexity in establishing clear micro-wear patterns for each action (*e.g.* cutting, scraping, sawing, whittling), activity (*e.g.* butchery, hide-working, woodworking, bone-working), and contact material (*e.g.* bone, wood, hide, plants, soft animal matter). This complexity arises from the fact that, in most of the cases, the micro-wear developed on different varieties of basalt used for the same task, over similar duration, and under similar experimental conditions, tended to exhibit notable variations and proved challenging to establish clear parameters. In particular, in our experimental studies, edge scarring was observed mainly in “finer” basalt during butchery and bone-working activities, while it was difficult to distinguish clear edge scarring on the “coarser” basalt. We believe that the mechanical properties, mineral composition, and fracture mechanics contribute to the differences in edge scarring development between the “finer” and “coarser” varieties of basalt. According to Lawn and Marshall’s (1979) definitions of isotropic and anisotropic materials, the “finer” basalt varieties (specifically basalt 3 in this study) exhibit relatively homogeneous fracture mechanics, leading to more uniform scars, and can be classified as isotropic. In contrast, the “coarser” basalts (basalts 1, 2, and 4) display the effects of applied force through or around numerous

large minerals, characterising them as anisotropic. Consequently, the force or stress applied to “coarser” basalt varieties tends to produce more irregular, less distinguishable scars and generally fewer scars compared to “finer” basalts. Striations were also predominantly developed on the “finer” basalt during butchery and dry hide scraping, while they were nearly absent on the “coarser” varieties. Small fragments of basalt or mineral particles breaking from the edge and coming into contact between the tool edge and the worked material are responsible for the formation of striations or linear features on the tool edge surface. However, it is surprising that the “coarser” basalt variety, which is more prone to the peeling or breakage of its minerals as observed in our experiments, shows almost no striations in most activities and with most worked materials. Richards (1988) attributes this phenomenon to the coarse and uneven surface of basalt, which can render the striations invisible. While this could be an explanation, we believe that using SEM should have revealed at least some traces of striations if they were present. Therefore, we need to investigate this matter further to understand why striations or linear features are almost absent on coarser varieties of basalt. Rounding and polish were prominent in dry hide-working across all basalt varieties, while they were absent or weakly developed in all other activities. We attribute this weak polish development to the continuous breakage or peeling of minerals. Each time this occurs, it removes part of the wear along with it. This process does not necessarily lead to dulling of the edge or surface fatigue. Instead, it generates relatively fresh surfaces through natural resharpening caused by the irregular breakage of minerals. These new surfaces come into contact with the worked material, developing some wear until the next cycle of mineral peeling. This behaviour may change with over 60 min of use, potentially leading to edge stabilisation and exhaustion. We plan to conduct further tests to investigate this behaviour. In this context, aligning with Richards’ perspective (1988), we agree that attributing specific rounding or polish types to particular contact material, as commonly observed with flint, is not suitable. The absence of clearly differentiable patterns, such as variations in texture or topography, impedes the establishment of such association.

The application of a multi-analytical approach, integrating both optical microscopy (OM) and scanning electron microscopy (SEM), has played a pivotal role in advancing our comprehension of micro-wear patterns on basalt tools. The efficacy of combining these distinct microscopic techniques has been underscored by various researchers (*e.g.* Asryan et al., 2014; Borel et al., 2014; Knutsson et al., 2015; Marreiros et al., 2015; Ollé et al., 2016; Pedernana et al., 2016b, 2018; Hayes et al., 2019; Martín-Viveros & Ollé, 2020; Wang et al., 2022). Regarding OM, both stereo zoom and metallographic microscopes have proven valuable in the comprehensive examination of basalt tools. These instruments were effective in raw material observation, enabling the evaluation of its colour, mineral presence, and overall macro- and some micro-wear features such as scars and rounding. Nevertheless, despite their utility, optical microscopes encountered limitations, particularly in observing specific micro-wear such as striations and polish on basalt. These traces, a pivotal micro-wear indicator for discerning tool motion, orientation, and contact material (Semenov, 1964; Keeley, 1980; Kamminga, 1982; Plisson, 1985; Mansur-Francomme, 1986; Richards, 1988), often proved elusive or indistinct under

conventional optical microscopes. The incorporation of the SEM into our analytical approach became indispensable in overcoming these challenges. Even at relatively low magnifications of the SEM (ranging from $\times 30$ to $\times 100$), the clear visualisation of these micro-wear traces was greatly facilitated. The higher magnifications (above $\times 200$) further enhanced their in-depth analyses. Furthermore, the utilisation of SEM has proven crucial in overcoming observation challenges arising from raw material variability and the high reflectivity of minerals, which otherwise hinder analysis and micro-wear observation under OM.

High-resolution casts are useful in micro-wear studies of lithic artefacts (Plisson, 1983; Rose, 1983; Bienenfeld, 1995; Banks and Key, 2003; Ollé and Vèrges, 2014). In this study, the casts served as a safeguard, ensuring that the original unused edges of our experimental tools were always preserved for potential future comparisons of specific spots or areas of the used and unused edges. Several key points are important to highlight: (1) Neither the silicon residues nor the “greasy shadow” resulting from the moulding material chemically alter the surface of basalt. (2) While challenging, it is possible to eliminate the remaining moulding residues from the tools’ surface through a repetitive but non-aggressive cleaning procedure. (3) Obtaining high-quality casts free of air pockets is challenging, especially with “coarser” varieties of basalt. However, by improving the silicone mixture for moulds and refining the application technique to ensure full coverage of the tool’s edge, including all mineral and irregular surfaces, it is possible to achieve better results. Additionally, enhancing the polyurethane resin mixture to ensure it is in the correct proportions and thoroughly fills all areas of the mould can result in high-quality casts with minimal or no air pockets. (4) For archaeological pieces, it is not ideal to create modern residues resulting from the application of moulding material or perform additional cleaning processes. However, in some cases (*e.g.* when transporting archaeological pieces from their location is impossible), making moulds and casts of the archaeological pieces is the only way to conduct micro-wear studies. Therefore, further investigation is needed to optimise the proportions for mixing moulding materials, improve techniques of applications, or find alternative silicon types for moulds or resin for casts, and improve non-aggressive cleaning methods to enhance efficiency without requiring repetitive application.

Different lavas, including basalt, are present in numerous prehistoric sites. Interestingly, at some sites, particularly those dating back to the Lower to Middle Pleistocene, basalt emerges as a predominant-sometimes exclusive-raw material for manufacturing lithic artefacts. As such, it is a key source of information about the hominin socioeconomic strategies and lifeways. Therefore, the application of micro-wear studies to lava/basalt assemblages, in conjunction with raw material, technological, and typological analyses, becomes imperative to enhance a comprehensive understanding of the archaeological record. As demonstrated in this work, micro-wear studies on basalt present inherent complexities and challenges. Our research serves as a significant methodological framework, aiming to undergo rigorous testing through the archaeological case assemblages mentioned earlier. Currently in the testing phase, it is noteworthy that the newly established experimental reference collection—encompassing a diverse range of basalt varieties and associated activities—combined with a multi-technique analytical approach integrating optical and

scanning electron microscopes, instills confidence in our ability to thoroughly examine and interpret archaeological assemblages.

Conclusions

The aim of this study was to contribute to the development of a methodological framework for the analysis of use-wear on basalt tools. The use of different basalt varieties, the construction of experimental reference collection, and the combined use of different microscopy techniques enhanced the robustness of our results.

Understanding the raw material properties, such as grain or mineral size, composition, and mechanical properties, is very important for understanding the edge deformation process and formation of different traces during their use. In our study, we observed distinct behaviour in basalts with finer and coarser minerals; the former demonstrated more efficiency but less durability, while the latter exhibited less efficiency but greater durability. However, establishing clear wear patterns for each motion, action, activity and contact materials across different basalt varieties proved challenging.

Building a comprehensive reference collection is a time-consuming yet essential step to understand basalt's behaviour in different activities. We started our experimental program with basalt varieties originating from different geographic regions and with activities designed to simulate common and well-recognised activities in prehistory. However, the experimental program is still ongoing, which implies a continuous expansion of the reference collection, encompassing additional experimental activities, worked materials, and a wider range of basalt varieties.

The sequential nature of experiments was useful for systematically monitoring and recording the development of use-wear traces at various stages of surface modification on different basalts. Notably, extended use revealed limited progression of use-wear traces, attributed to continuous mineral breakage especially on “coarser” varieties of basalt.

The combined use of optical and scanning electron microscopes has played a pivotal role in advancing our understanding of micro-wear patterns on basalt tools. While the OM, proved effective in macro- and some micro-wear observations, it encountered limitations in detecting specific micro-wear features like striations and polish. The incorporation of SEM proved indispensable in overcoming these challenges, allowing clear visualisation and analysis of these traces even at relatively low magnifications. Higher magnifications further enhanced their in-depth analysis.

Cleaning basalt tools presented unique challenges due to their chemical composition, especially the presence of calcium in plagioclase minerals. We established a careful cleaning protocol involving ultrasonic baths with a neutral phosphate-free detergent, a rinse with running tap water, and a final bath in pure acetone. The use of a diluted hydrogen peroxide (H₂O₂) solution has also demonstrated its effectiveness in efficiently eliminating organic residues from basalt tools.

Obtaining high-resolution casts for basalt is challenging, especially with “coarser” varieties. However, high-quality casts with minimal air pockets can be achieved by refining silicone mixtures and application techniques. While cleaning

silicone residues from basalt surface is difficult, it is achievable with a thorough cleaning protocol.

Finally, our research serves as a pivotal methodological framework, providing access to functional evidence for a raw material that had remained largely inaccessible up to now. It currently undergoes rigorous testing on archaeological lithic artefacts, promising advancements in the thorough examination and interpretation of archaeological lithic assemblages.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10816-024-09663-8>.

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Author Contribution L.A. and V.R. conceptualized the study. L.A. and V.R. designed the methodology. L.A. conducted formal analysis and wrote the main manuscript text and prepared all figures. L.A. and V.R. reviewed and edited the manuscript. L.A. and V.R. acquired funding for the project. V.R. provided supervision.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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