Exploring the production of lithic instruments at Mahal Teglinos (Eastern Sudan): An experimental approach for the characterisation of residues, macro and micro traces derived from the knapping on anvil technique of quartz, quartzite and chert pebbles and cobbles

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Abstract:

Despite the existence of intense research focused on the characterisation of macro traces derived from the use of the knapping on anvil technique, little attention has been dedicated to the detection of micro technical traces and residues on blanks and cores produced by means of this knapping technique. Macro technical traces derived from the knapping on anvil technique were detected on stone artefacts from the Gash Group's lithic assemblage (middle III - early II millennium BCE) at Mahal Teglinos (K1), located in the modern region of Kassala in Eastern Sudan. An experimental programme, was developed to localise macro and micro manufacturing traces and residues from this knapping technique, using pebbles and small cobbles of quartz, quartzite and chert to create a reference collection for the interpretation of archaeological material. The methodology, adopted for this study, involved the combined use of several microscopes for traceological and residue analyses. Stereo and 3D digital microscopes have been utilised to characterise macro technical traces and locate possible residues. The elemental chemical composition of the residues has been characterised trough scanning electron microscopy (SEM) using energy dispersive X-ray (EDS) and element maps. The association of macro and micro traces (evidence of polishing and striations) identified on the experimental materials enabled the comparison and detection of similar technical traces on some archaeological material, as there are cases in which similar macro traces may result from direct percussion knapping. Our experiment demonstrated that macro traces are present on nearly all stone artefact replicas, while residues develop more easily on stone artefacts with specific characteristics of the butt and counter-butt of flakes and striking and resting platform of cores. Micro-technical traces confirm that blanks and cores were produced using the knapping on anvil technique when macro traces characteristics of this knapping technique are present on stone artefacts within a lithic assemblage, while residues indicate the lithology of the used hammerstone and anvil.

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1. Introduction

During the study of a set of stone artefacts from the lithic assemblage from Mahal Teglinos (K1), Eastern Sudan, macro technical traces derived from the knapping on anvil technique were observed on small cores, blanks and tools made from several raw materials. To test our hypothesis, we developed an experimental programme to characterise macro and micro-technical traces, as well as to locate and characterise the elemental composition of residues allowing for the detection of stone utilised for the hammerstones and anvils. Lastly, we tested our results to ensure that we had valid criteria for finding them in the archaeological record.

The knapping on anvil technique was identified over a century ago (Bardon *et al.* 1906; Teit 1900: 182). It has since been given several definitions (Breuil & Lantier 1951: 71-72; Callahan 1987: 13; Crabtree 1972: 10-11; Hiscock 2015; Jeske 1992) but a general consensus is still to be reached. Breuil & Lantier (1951: 71-72) defined the "bipolar technique of percussion on an anvil" as a flaking technique involving the use of a hammerstone held by hand to strike a stone positioned upon an anvil. This technique may, owing to the use of using different knapping methods, generate stone artefacts showing several features creating confusion in their classification. Hiscock (2015) further argued that the "bipolar blows" are created by striking (with a hammerstone) a stone in line with the point at which it is in contact with the anvil. In cases involving a counterstrike, Mourre (1996a; 2004) distinguishes between axial knapping on an anvil (where the strike and the counterstrike are situated on the same axis) and the non-axial version (where the two impacts are not on the same axis). We observed in our experiment that there are different forms of blank detachments and features deriving from the same gesture. A few features are similar to those observed on blanks cause by the use of the hand held technique creating confusion in their classification. For this reason, in this paper, we use the Hiscock's (2015) definition of "bipolar knapping" for stone artefacts showing impact point and counterstrike and "anvil-rested non-bipolar" for those showing only one of the different stigmas derived from this knapping technique.

The earlier stone artefacts made using the knapping on anvil technique come from Lomekwi 3 in Kenya and dated to 3.3 Ma (Harmand *et al.* 2015). This knapping technique is chronologically and geographically widespread. It has been recognised as feature in African lithic assemblages (Barsky *et al.* 2011; Delagnes *et al.* 2023; Diez Martin *et al.* 2011; Eren *et al.* 2013; Gallotti *et al.* 2020; Garcia *et al.* 2013; Gurtov & Eren 2014; Kimbel *et al.* 1996; de la Peña & Wadley 2014; van Riet Lowe 1946; Soriano *et al.* 2010; Tabrett 2017; de la Torre 2004). It was also attested at Pleistocene (Bourguignon *et al.* 2016; Collina *et al.* 2020; Grimaldi *et al.* 2020; de Lombera-Hermida *et al.* 2016; Mourre *et al.* 2010; Moyano *et al.* 2011; de la Peña & Toscano 2013; Titton *et al.* 2021) and Holocene (Ballin 1999; Callahan 1987; Driscoll 2010; Roda Gilabert *et al.* 2015) European sites. Recent studies documented its occurrence in Asia as well (Gao 2000; Li *et. al* 2017; de Lumley *et al.* 2005; Ma *et al.* 2020; Moore *et al.* 2009; Ryassert 2005; Wedage *et al.* 2019; Yang *et al.* 2016; Zaidner 2014). Lithic artefacts made from this knapping technique were found in Oceania (Flenniken & White 1985; Hayden 1979; Theden-Ringl 2017; White 1968) as well as North (Binford & Quimby 1963; Flenniken 1980; Goodyear 1993; Odell 2000; Shott 1999) and South America (Boëda *et al.* 2014; Curtoni 1996; Duarte-Talim 2015; Miller 1979; Prous & Alonso 1990). For an updated list of sites which have stone artefacts made with "knapping on anvil reduction" in their lithic assemblages, see Horta *et al.* (2022).

Ethnographic research carried out in Africa (Barham 1987; Gallagher 1977; Masao 1982; Weedman Arthur 2010), Asia (Kosambi 1967), Australia (Hayden 1979), New Guinea (Sillitoe & Hardy 2003; Watson 1995; White 1967), and in Northern (Bradbury 2010; Honea 1965; Shott 1989) and Southern America (Curtoni 1996; Duarte-Talim 2015), has demonstrated the variability of stone artefacts made with the knapping on anvil technique and their suitability for the execution of different activities. For more ethnographic works, see Yeşilova *et al.* 2024.

During the last decades, studies concerning the identification of macro technical traces on chert (Bietti *et al.* 2010; Cancellieri *et al.* 2001; Donnart *et al.* 2009; Faivre *et al.* 2010; Grimaldi *et al.* 2007; de la Peña 2015b), quartz (Pargeter & de la Peña 2017; de la Peña 2015b), quartzite (Byrne *et al.* 2015; Yeşilova *et al.* 2024), trachydacite (Kuijt *et al.* 1995) and other lithotypes (Sánchez-Yustos *et al.* 2017) that were knapped on an anvil have been performed.

Other studies have also focused on reduction strategies (Bialowarczuk 2015; Goodyear 1993; Gurtov *et al.* 2015; Jeske & Lurie 1993; Kobayashi 1975; Leaf 1979; Li *et al.* 2017; Pargeter & Eren 2017; Pargeter *et al.* 2019; de la Peña & Wasley 2014) or dealt with the function of stone artefacts derived from the use of this knapping technique (Bader *et al.* 2015; Crovetto *et al.* 1994; Devriendt 2011; Flenniken 1980; Gibaja *et al.* 2007; Hayden 1980; Igreja & Porraz 2013; Jeske & Sterner-Miller 2015; Kolobova *et al.* 2021; Langejans 2012; LeBlanc 1992; Lucas & Hays 2004; de la Peña 2011; Shott 1999).

Despite the existence of this research, it is, to our knowledge, rare that studies focus on characterising micro technical traces and residues produced by the anvil (Vergès & Ollé 2011), hammerstones (Rots 2010a; 2010b; Touzé & Rots 2025) and on the effects of production processes on stone tools by retouching (Byrne *et al.* 2006) and backing (Fasser et al. 2024) them with retouchers made from different materials. Hammerstones smears were also mentioned by Keeley (1980: 20) and Mansur-Franchomme (1986: 158 & 214-215).

1.1. The site of Mahal Teglinos

Mahal Teglinos (K1) was first recognized in 1917 by John Winter Crowfoot (1928). The site is located at the northern end of the Jebel Taka, near the modern town of Kassala in eastern Sudan (Figure 1).

The Italian Archaeological Expedition to the Sudan, Kassala (IAESK), directed by Rodolfo Fattovich, carried out systematic investigations from 1980 to 1995 (Coltorti *et al.* 1984; Costantini *et al.* 1982; Cremaschi *et al.* 1986; Fattovich 1990; 1993; Fattovich *et al.* 1994). The Italian Archaeological Expedition to the Eastern Sudan of the University of Naples “L’Orientale” (IAEES), resumed the archaeological investigation in 2010 (Manzo 2017 and references cited therein; 2018; 2019). Mahal Teglinos was inhabited from the 4th millennium BCE up to the 1st millennium CE. The main occupation phase (Figure 2a), dating to the Gash Group period (ca mid-3rd - early 2nd millennium BCE), is characterised by two living areas (Figure 2b) and two cemeteries marked by monolithic *stelae* (Fattovich 1987; 1989; Manzo 2006) in the central and Eastern part of the site (Figure 2c).

Despite stone tools being one of the most recovered archaeological artefacts, few studies have been performed so far about micro (Costantini *et al.* 1982; Phillipson 2017; Usai 1995; 2002) and macro lithic tools (Rega 2020a; 2020b; Rega *et al.* 2021). Recent geoarchaeological investigation have nevertheless added relevant information about the geological history of the site (Costanzo *et al.* 2021; 2022). For a better understanding of the role of the site in the Eastern Sudan and relations with other areas of the Nile Valley and Horn of Africa see Manzo (2012; 2017; 2020).

Figure 1. Location of Mahal Teglinos, eastern Sudan.

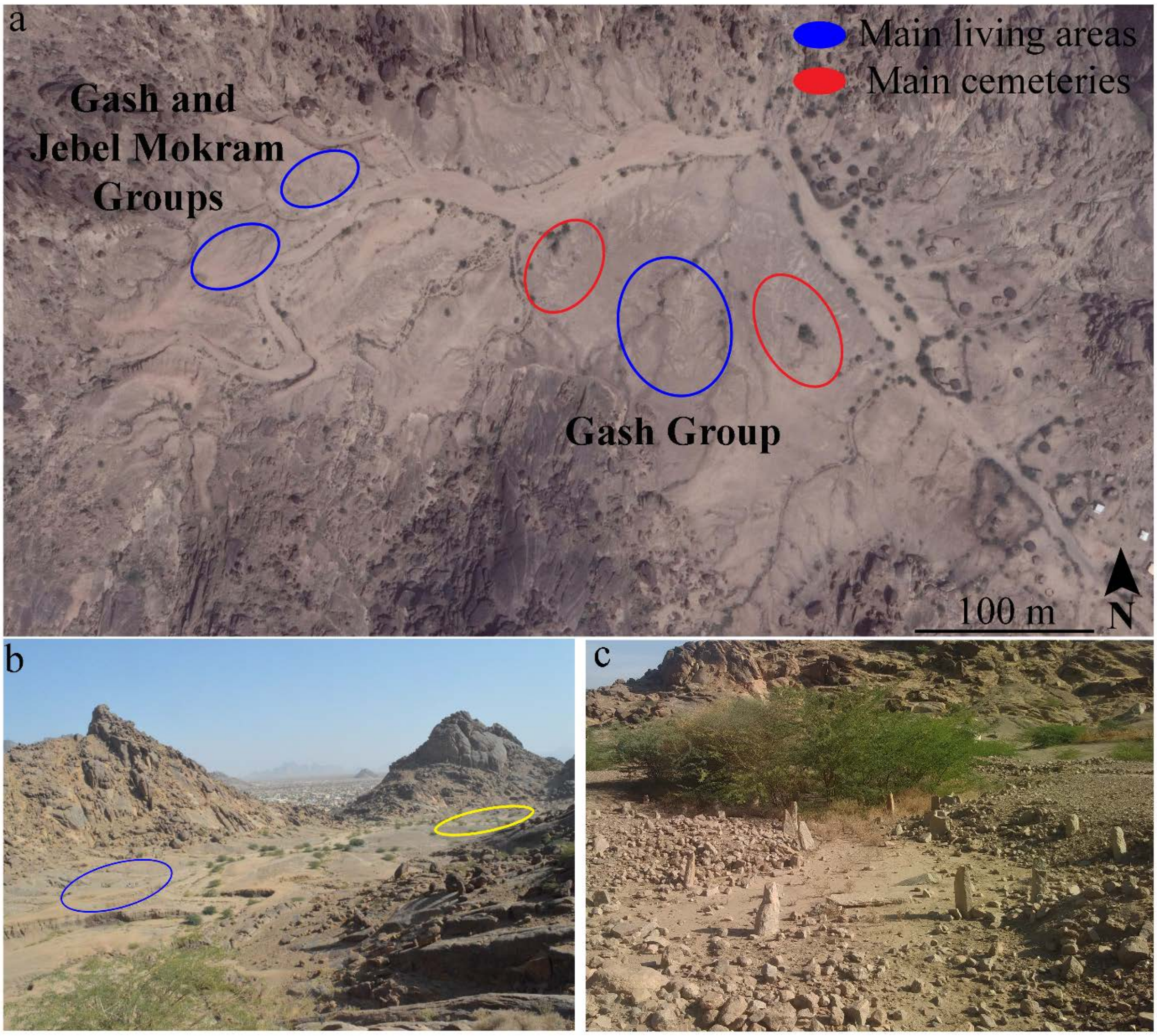

Figure 2. A) general view of Mahal Teglinos; b) living areas; c) particular of Eastern cemetery and stelae.

2. Materials and Methods

2.1. Mahal Teglinos lithic artefacts

The lithic sample comes from the Gash Group's settlement and cemetery areas, investigated during the 1980s and 1990s. The samples comprises 209 stone artefacts representing approximately 2% of the overall Gash Group's lithic assemblage. The sample includes cores (12.4%) and core fragments (1.9), blanks (34%) and blank fragments (12%), tools (27.3%) and tool fragments (11%) and chunks (1.4%). For core types across lithotypes, see Table 1 & Supplementary file 1: figures 1-3; for their average dimensions, see Table 2; and for knapping on anvil macro technical traces, see Figure 3.

Table 1. Knapping methods detected on cores from Mahal Teglinos: a) knapping on anvil, b1) bipolar axial, b2) bipolar non-axial and c) anvil-rested non-bipolar.

Lithotypes	**Type of cores**	**Knapping technique**			**Total**
		A			
		B1	**B2**	**C**	
Chert (n = 12)	Two-platform cores	-	-	1	1
	Exhausted one-platform cores	3	-	-	3
	Cores on flakes	5	1	-	6
	Core fragments	2	-	-	2
Quartz (n = 14)	One-platform cores	-	-	1	1
	Multiple-platform cores	1	-	-	1
	Exhausted one-platform cores	4	-	-	4
	Casual cores	1	-	3	4
	Cores on flakes	1	-	1	2
	Core fragments	2	-	-	2
Chalcedony (n = 2)	One platform micro-cores	1	-	-	1
	Two platforms micro-cores	-	-	1	1
Agate (n = 1)	Casual cores	-	-	1	1
Basalt (n = 1)	Casual cores	-	-	1	1
Total		**20**	**1**	**9**	**30**
%		**66.7**	**3.3**	**30**	**100**

Table 2. Univariate statistic of dimensions of the cores from Mahal Teglinos.

		Length (mm)	**Width (mm)**	**Thickness (mm)**	**Weight (gr)**
Core on flakes	N	8	8	8	8
	Min	19.6	15	7.2	2.4
	Max	38.3	37.4	13.6	20.7
	Mean	26.63	24.23	9.23	6.85
	Stand. dev	6.3	7.37	2.14	6.14
Other cores	N	18	18	18	18
	Min	13.5	7.6	5.9	0.6
	Max	38.4	61.8	78.2	227.1
	Mean	24.9	27.48	22.51	27.62
	Stand. dev	7.67	11.97	16.86	51.15

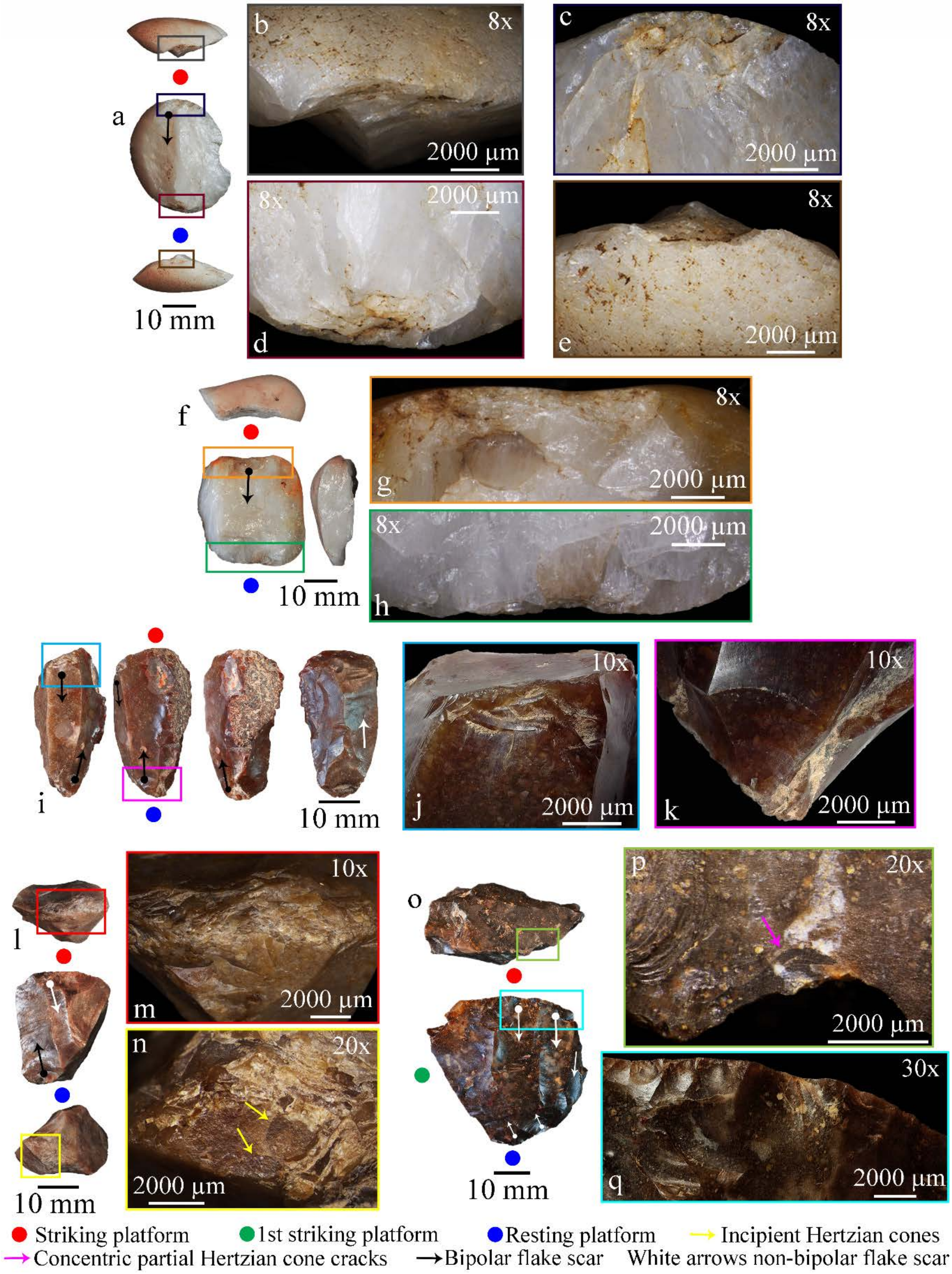

Figure 3. Quartz (a & f) and chert (i, l & o) bipolar axial core on flake (a) bipolar axial exhausted core (f, i & l) and anvil-rested non-bipolar two platforms core (o) from Mahal Teglinos showing different knapping on anvil macro technical traces: b & e) notching; c) cascade; d & g) crushing; h) crushing and overlapping macro and micro scars; j) overlapping micro scars; k) Hertzian cone; m) blunting and cascade; n) incipient Hertzian cones and cascade; p) notching and concentric partial Hertzian cone cracks and q) not overlapping macro and micro scars. The green dot indicates the first striking platform when a core has been rotated (o), whereas the red indicates the last striking platform.

Three un-knapped quartz pebbles measuring less than 40 mm in length (Supplementary file 1: figure 2a-c) were found in the western living area in 2019. For the description of technological attributes and macro technical traces of the cores, see Supplementary file 1: tables 1-18. Excluding the cores and core fragments, 43% of the lithic artefacts (Table 3) show knapping on anvil technique marks (Figure 4), whereas 11.2 % are hand-held products. The remaining 44.7% was classified as indeterminate because it was not possible to distinguish the knapping technique, and 1.1 % included formal tools made from natural rock fragments.

Table 3. Knapping techniques detected on blanks and stone tools across artefact classes and lithotypes from Mahal Teglinos: a) knapping on anvil, b1) bipolar axial, b2) bipolar non-axial, c) anvil-rested non-bipolar, d) hand-held, e) indeterminate, f) natural fragment. The asterisk (*) indicates that a tool is made from a natural rock fragment.

Lithotypes	**Artefact Class**	**Knapping technique**						**Total**
		A			**D**	**E**	**F**	
		B1	**B2**	**C**				
Chert (n = 65)	Flakes and fragments	3	1	12	11	5	-	32
	Blades, bladelets and fragments	-	-	2	1	1	-	4
	Backed pieces	-	-	-	-	2	-	2
	Tools and fragments	1	-	7	1	15	-	24
	Chunks	-	-	-	-	3	-	3
Chalcedony (n = 51)	Flakes and fragments	1	1	6	4	2	-	14
	Blades, bladelets and fragments	-	-	2	-	2	-	4
	Backed pieces and fragments	-	-	4	-	-	-	4
	Tools and fragments	-	-	6	1	21	-	28
	Indeterminate fragment	1	-	-	-	-	-	1
Agate (n = 12)	Flakes	1	-	3	1	1	-	6
	Tools and fragments	-	-	1	-	5	-	6
Quartz (n = 30)	Flakes and fragments	7	3	8	1	6	-	25
	Blades, bladelets and fragments	-	-	1	-	-	-	1
	Tools and fragments	-	-	1	-	3	-	4
Quartzite (n = 6)	Flakes	1	-	-	-	2	-	3
	Tools	-	-	2	-	1	-	3
Basalt (n = 10)	Flakes and fragments	-	-	-	-	3	-	3
	Tools and fragments	-	-	-	-	6	1*	7
Uncertain hornfels	Flakes	-	-	-	-	1	-	1
(n = 2)	Tools and fragments	-	-	1				1
Siliceous rock (n = 1)	Flake fragment	-	-	1	-	-	-	1
Limestone (n = 1)	Tools	-	-	-	-	-	1*	1
Obsidian (n = 1)	Flake fragments	-	-	-	-	1	-	1
Total		**15**	**5**	**57**	**20**	**80**	**2**	**179**
%		**8.4**	**2.8**	**31.8**	**11.2**	**44.7**	**1.1**	**100**

Figure 4. Quartz (a & d), quartzite (h), chert (k, n & q) and chalcedony (s) flakes (a, d, h, k & n) and borers (q & s) from Mahal Teglinos showing different knapping on anvil technical macro traces: b, c & m) crushing; e & g) overlapping micro scars; f) sheared bulb; i & j) overlapping macro and micro scars; m) collapsed striking platform showing negative crushed bulb; o) macro scar; p) crushing and overlapping macro and micro scars; r) crushed flat bulb and t) diffuse Hertzian cone.

Lithic artefacts made with an undetectable knapping technique, because their retouching or use removed knapping macro technical traces on the proximal and distal parts include tools (n = 35), tool fragments (n = 13), backed pieces (n = 3) and backed piece fragments (n = 1). They also comprise complete blanks (n = 11), showing attributes that can be found with both knapping techniques. They include primary flakes (*entame*) with slightly convex and convex plain or linear cortical butts (Gallotti *et al.* 2020; Hayden 1980) or non-cortical plain butts with a flat profile, showing or not showing impact marks, and having non-axial termination (Supplementary file 2: figure 2a & b). Furthermore, indeterminate lithic artefacts include blank fragments missing the proximal or distal end (n = 13) and chunks (n = 3).

Complete blanks (n = 71) include flakes (n = 67), bladelets (n = 2) and blades (n = 2). Among the blanks (Supplementary file 2: figure 1), "lemon slice" flakes (Bialowarczuk 2015: fig. 3-5) occur (n = 11) (Supplementary file 2: figure 2). 23.9% of the blanks show bipolar marks, and 35.2% show feature marks belonging to the knapping on an anvil, while 25.4% are hand-held, and 15.5% have been classified as indeterminate. For their technological attributes and attribute types, see Supplementary file 2: tables 1-22. The mean dimensions of the complete blanks do not differ significantly based on their knapping technique (Table 4).

Table 4. Univariate statistics of the size of complete blanks from Mahal Teglinos.

Blanks		**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Weight (gr)**
Bipolar axial & non-axial	N	17	17	17	17
	Min	12.7	11.8	3.4	1
	Max	43.4	31.6	19.4	24.6
	Mean	25.2	21.6	8.27	5.54
	Stand. dev	8.43	5.66	4.19	5.97
Anvil-rested non-bipolar	N	25	25	25	25
	Min	14.6	6.6	2.6	0.4
	Max	33.7	30.4	13.9	8.6
	Mean	22.1	19.2	6.61	2.7
	Stand. dev	5.92	6.33	2.67	2.15
Hand-held	N	18	18	18	18
	Min	12.8	12.2	2.9	0.3
	Max	40.5	41.3	13.6	11.8
	Mean	27.43	23.53	7.49	5.12
	Stand. dev	8.14	8.42	2.86	3.69
Indeterminate	N	11	11	11	11
	Min	11.7	6	3	0.2
	Max	46	39.4	13.1	13.4
	Mean	27	25.03	8.17	6.25
	Stand. dev	8.93	9.64	3.19	4.25

Stone tool types are listed in Figure 5. For their sizes, they may be classified as microlithic tools, having an average length of 20.54 ± 12.74 mm. The average sizes of the complete intentionally knapped stone tools (Table 5a) decrease excluding a side scraper and a denticulate made from natural stone fragments (Table 5b).

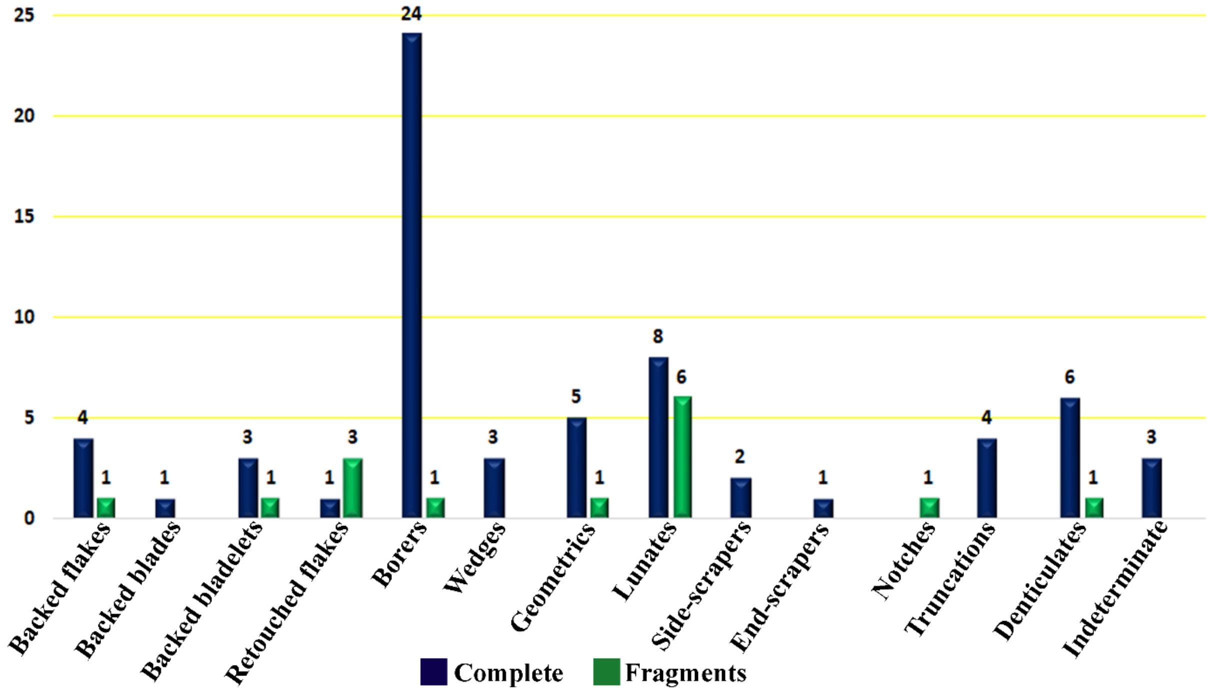

Figure 5. Stone tool types from Mahal Teglinos.

Table 5. Univariate statistics of complete tools from Mahal Teglinos.

Complete tools		Length (mm)	Width (mm)	Thickness (mm)	Weight (gr)
A	N	65	65	65	65
	Min	9.4	5.8	2	0.1
	Max	82.9	63.8	20.5	120.7
	Mean	20.54	16.42	5.79	5.51
	Stand. dev	12.74	10.84	3.14	18.6
B	N	63	63	63	63
	Min	9.4	5.8	2	0.1
	Max	41.5	31.6	15.3	16.1
	Mean	18.65	14.92	5.41	2.29
	Stand. dev	7.10	6.87	2.28	3.34

2.2. Experimental knapping and data recording

Chert pebbles and cobbles (Supplementary file 3: figure 1) were collected from the Gargano plain (Puglia), while chert nodules were collected from the Rotzo Formation (Veneto). Quartz and quartzite pebbles and cobbles, used as cores, and dolomite, quartz, sandstone, porphyritic rock and basalt cobbles, utilised as hammerstones and anvils (Supplementary file 3: figures 2 & 3) were sourced from the Mella River (Brescia), because the last field season at Mahal Teglinos was conducted in 2019 due to Covid restrictions and the political crisis in Sudan.

One of the authors (D.C.) performed the experimental knapping using 30 quartz, 19 quartzite and 23 chert pebbles and cobbles. Different phases of core reduction (removing flakes up to exhausted and split cores) were reached to have different core types, and blanks with at least one cutting edge, as observed in the Mahal Teglinos assemblage. Blows were struck at about 90 degrees. Pebbles or cobbles were vertically placed on the anvil following the length, width or thickness axis, the latter defined as "anvil-assisted" by Pargeter & Tweedie (2018), to collect variations in data depending on the position of the core

(Supplementary file 3: figure 4). We did not conduct tangential strikes, *i.e.*, retouching on the anvil or oblique flaking. Seven cores (Exp. 2, 4, 5, 14, 20, 43 and 44) were rotated, generating two or three knapping axes. When a core shows multiple striking or resting platforms, only the last striking and resting platforms are described. This decision is based on the observation that, during the knapping process, detaching flakes may also remove the previous resting platform of the core (Supplementary file 4: figure 1g & figure 2d & e), thus preventing their description, as also seen on the archaeological cores (Supplementary file 2: figure 2e & f). A pebble (Exp. 47) and two cobbles (Exp. 49 and 60) were split into two and three chunks, which were then used as cores. The number of strikes for a flake detachment and where it came from was recorded. Each blank was put in a plastic bag. Its length, width, thickness, and weight were measured using sterile, powder-free gloves to avoid contamination from handling (Ollé *et al.* 2016; Pedergnana *et al.* 2016). Eighteen blanks have been hand-held knapped from two chert nodules with a prepared striking platform to compare the different types of macro and micro technical traces and the pattern of residues formation on their butts with the specimens made from the knapping on anvil technique. We also tested the efficacy of the hand-held percussion on three chert, a quartzite and a basalt small cobbles without preparing a striking platform using a quartzitic sandstone and a quartzite hammerstones (Supplementary file 3: table 1).

The technological attributes and attribute types of products made from ten chert, ten quartz, and ten quartzite pebbles or cobbles were analysed, as shown in Table 6. For the characteristics of the analysed pebbles and cobbles, see Supplementary file 3: table 2.

2.3. Experimental technical traces and residues characterisation

Our protocol combined the use of several microscopes for characterizing residues, macro and micro technical traces. The selected experimental materials were analysed as follows:

1) residue distribution and macro technical traces were recorded at low magnifications before their cleaning, using single images with Lupa Euromex stereomicroscope (8x-30x) and stitching technology of Hirox KH-8700 3D digital microscope (35-50x). To create panoramic images featuring the horizontal stitching of the Lupa Euromex stereomicroscope, the Composite Image Editor (CIE) or AutoStich software were employed;

2) the elemental composition of residues was investigated using Energy-dispersive X-ray spectroscopy (EDS) through points of interest spectra and element distribution maps with scanning electron microscopes (SEM JEOL 6400 and environmental ESEM Fei Quanta 600 both equipped with secondary electron Everhart-Thornley (ETD) and back-scattered electron (DualBSD) detectors). The SEM magnification was from 200x to 2500x;

3) polishing traces and striations characterisation were performed using an optical ZEISS Axioscope A1 metallographic microscope equipped with Differential Interference Contrast, Nomarski prisms and magnification from 50x to 500x. Striations of three experimental pieces and one archaeological artefact were studied using the ESEM Fei Quanta 600.

The cleaning protocol followed the one established by previous studies (Ollé & Vergès 2014; Pedergnana *et al.* 2016). Industrial pure acetone (99.9%) was used for 5 to 20 minutes before the EDS analysis to remove possible modern contamination (finger fat and human skin residues). Hydrogen peroxide (H_20_2) at 92% was used after the EDS analysis and characterisation of the striation types to remove residues and to seek possible polishing traces left by contact with the hammerstone and anvil. The cleaning in an ultrasonic bath with H_2O_2 lasted between 10 and 60 minutes depending on the strength of the bond between the residues and the stone artefacts' surfaces (Byrne *et al.* 2006; Cnuts & Rots 2018).

Table 6. Technological attributes and attribute types recorded on experimental and archaeological knapping on anvil products.

Technological Categories	1. Flake; 2. Flake fragment; 3. Blade; 4. Blade fragment; 5. Bladelet; 6. Bladelet fragment; 7 Core; 8. Shatter; 9. Chunk
Originated core and blank	1. Bipolar axial; 2. Bipolar non-axial; 3. Anvil-rested non-bipolar; 4. Split
Technological Attributes	**Attribute Type**
Cortex amount	1. Primary; 2. Secondary < 50%; 3. Secondary >50%; 4. Tertiary
Scar direction	1. Unidirectional from striking platform; 2. Unidirectional from resting platform; 3. Opposite; 4. Orthogonal; 5. Convergent from striking or resting platform; 6. Opposite convergent; 7. Centripetal; 8. Multidirectional; 9. Indeterminate; 10. Absent
Profile	1. Straight; 2. Slightly convex; 3. Convex; 4. Slightly concave; 5. Concave; 6. Slightly sinuous; 7. Sinuous; 8. Irregular; 9. Twisted; 10. Indeterminate (because broken)
Shape	1. Sub-rectangular; 2. Rectangular; 3 Sub-square; 4. Square; 5. Sub-ovate; 6. Ovate; 7. Sub-circular; 8. Circular; 9. Sub-triangular; 10. Triangular; 11. Irregular
Termination	1. Axial; 2. Feather; 3. Step; 4. Hinge; 5. Plunge; 6. Broken
Type of fracture	1. Siret; 2. Bending; 3. Transversal; 4. Uneven
Cortex amount on core striking - resting platform and blank butt - counter-butt	1. Cortical; 2. Semi-cortical; 3. Non-cortical; 4. Indeterminate (broken butt or counter-butt)
Morphological categories of the core striking - resting platform and blank butt - counter-butt	1. Plain; 2. Linear; 3. Punctiform; 4. Winged; 5. Collapsed; 6. Broken
Core striking - resting platform and blank butt - counter-butt delineations	1. Flat; 2. Slightly convex; 3. Convex; 4. Slightly concave; 5. Concave; 6. Slightly sinuous; 7. Sinuous; 8. Irregular; 9. Indeterminate (broken butt or counter-butt)
Macro traces on the core striking - resting platform and blank butt - counter-butt	1. Crushing; 2. Blunting; 3. Notching; 4. Incipient Hertzian cone; 5. Double incipient Hertzian cone; 6. Multiple incipient Hertzian cones; 7. Concentric partial Hertzian cone cracks; 8. Whitening; 9. Cracks; 10. Combination of macro traces; 11. Indeterminate (broken butt or counter-butt); 11. No signs
Core and blank proximal (hammer strike) and distal bulb (counter-strike) types	1. Flat; 2. Positive. 3. Positive prominent; 4. Positive diffuse; 5. Hinge; 6. Hertzian cone; 7. Double Hertzian cone; 8. Multiple Hertzian cones; 9. Crushed; 10. Sheared; 11. Double sheared; 12. Negative; 13. Negative crushed; 14. Negative spike-shaped; 15. Negative spike-shaped crushed; 16. Dihedral; 17. Dihedral crushed; 18. Indeterminate (broken butt or counter-butt); 19. No bulb
Macro traces on the ventral and dorsal surface of the proximal and distal end of cores and blanks	1. Crushing; 2. Cascade; 3. Hertzian cone; 4. Double Hertzian cone; 5. Multiple Hertzian cones; 6. Whitening; 7. Macro scar; 8. Micro scar; 9. Not overlapping macro scars; 10. Not overlapping micro scars; 11. Overlapping macro scars; 12. Overlapping micro scars; 13. Combination of macro traces; 14. Indeterminate (broken butt or counter-butt); 15. No signs
Residues and striations on striking - resting platform and butt - counter-butt	1. Yes; 2. No

3. Results

Bipolar axial (Hiscock 2015; Mourre 1996a; Vergès & Ollé 2011) and non-axial (de Lombera Hermida *et al.* 2016; Mourre 1996a; Vergès & Ollé 2011) cores and blanks (defined compression flakes in Cotterell & Kamminga (1987) as well as anvil-rested non-bipolar cores and blanks (Hiscock 2015) were produced during our experiment. Additionally, shatter, chunks, and debris occurred. Excluding debris, the experimental products are listed in Table 7.

Table 7. Experimental products across artefact classes and lithotypes.

	Chert	Quartz	Quartzite	Total	%
Cores					
Bipolar axial	8	5	7	20	60.6
Bipolar non-axial	4	2	2	8	24.2
Anvil-rested non-bipolar	1	1	1	3	9.1
Split	-	2	-	2	6.1
Total	**13**	**10**	**10**	**33**	**100**
Blanks					
Bipolar axial flakes	24	16	15	55	21.2
Bipolar non-axial flakes	21	7	6	31	13.1
Anvil-rested non-bipolar flakes	68	8	16	94	35.5
Bipolar axial flake fragments	-	4	2	6	2.3
Bipolar non-axial flake fragments	1	2	1	4	1.5
Anvil-rested non-bipolar flake fragments	1	2	-	3	1.2
Bipolar axial orange segments	3	4	7	14	5.4
Bipolar non-axial orange segments	-	-	1	1	0.4
Bipolar axial orange segment fragments	-	2	1	3	1.2
Bipolar axial “lemon slice” flakes	2	4	1	7	2.7
Anvil-rested non-bipolar “lemon slice” flakes	-	1	-	1	0.4
Bipolar axial bladelets	-	1	1	2	0.8
Anvil-rested non-bipolar bladelets	9	2	7	18	6.9
Anvil-rested non-bipolar bladelet fragments	1	-	2	3	1.2
Bipolar axial blades	3	-	1	4	1.5
Anvil-rested non-bipolar blades	3	-	-	3	1.2
Shatter	2	-	1	3	1.2
Chunks	6	-	-	6	2.3
Total	**144**	**53**	**62**	**259**	**100**

3.1. Cores attributes and macro technical traces

In describing the striking and resting platform attributes, some of the terms used for the description of flakes were adopted. For core examples see Supplementary file 4: figures 1-3, and for their knapping position, size, weight and the number of knapped blanks see Table 8.

Table 8. Experimental cores: BP = bipolar; ARNB= anvil-rested non-bipolar; P = knapping position; 1 = vertical longitudinal; 2 = vertical transversal; 3 = anvil-assisted; TC = type of core generated; A = one striking platform; B = two striking platform; L = length; W = width; T = Thickness; We = weight; TB = total detached blanks.

Core ID	BP	ARNB	P	TC	L (mm)	W (mm)	T (mm)	We (gr)	TB
Chert									
Exp. 44	Y	N	1 & 2	B	42.2	49.0	18.0	28.1	5
Exp. 47.1	Y	N	3	A	38.9	31.6	26.2	35.0	10
Exp. 47.2	Y	N	3	A	35.8	45.1	20.5	38.6	3
Exp. 49.1	Y	N	3	A	32.8	29.8	24.3	25.4	13
Exp. 50	Y	N	2	A	38.4	29.1	17.3	23.0	10
Exp. 55	Y	N	3	A	26.9	45.2	30.7	29.5	24
Exp. 59	Y	N	2	A	35.4	33.8	21.2	21.3	20
Exp. 60.1	Y	N	2	A	40.8	38.9	17.9	29.1	6
Exp. 60.2	Y	N	2	A	28.2	31.1	14.2	11.6	10
Exp. 60.3	Y	N	2	A	41.4	71.0	24.1	78.2	3
Exp. 61	Y	N	1	A	26.5	23.2	10.4	6.4	8
Exp. 62	N	Y	1	A	33.8	41.2	14.2	16.3	13
Exp. 71	Y	N	1	A	26.0	22.8	18.1	10.5	21
Quartz									
Exp. 9	Y	N	2	A	38.3	32.4	23.5	24.8	7
Exp. 13	Y	N	1	A	42.0	30.6	19.9	33.0	2
Exp. 14	Y	N	1 & 3	B	22.4	22.7	18.9	11.8	8
Exp. 15	Y	N	3	A	32.6	37.8	28.3	49.9	3
Exp. 17	Y	N	1	A	-	-	-	-	3
Exp. 20	Y	N	1 & 3	B	31.7	25.7	20.1	24.0	10
Exp. 30	Y	N	1	A	-	-	-	-	3
Exp. 31	N	Y	1	A	36.1	21.1	10.8	7.1	4
Exp. 35	Y	N	2	A	42.6	41.6	16.6	37.1	9
Exp. 67	Y	N	1	A	55.6	29.9	21.0	39.0	4
Quartzite									
Exp. 1	Y	N	1	A	38.4	26.7	10.5	14.7	4
Exp. 2	Y	N	2, 3 & 1	A	22.0	20.5	12.3	8.3	9
Exp. 3	Y	N	1	A	38.2	32.6	15.2	27.9	2
Exp. 4	Y	N	2 & 1	A	44.6	32.0	21.6	24.6	4
Exp. 5	N	Y	1 & 3	A	45.4	35.2	34.0	64.2	10
Exp. 6	Y	N	2	A	32.6	35.0	29.2	35.4	10
Exp. 25	Y	N	1	A	36.4	32.0	18.1	20.1	2
Exp. 37	Y	N	1	A	33.4	19.9	24.5	18.3	6
Exp. 42	Y	N	1	A	31.2	25.8	14.0	13.1	7
Exp. 43	Y	N	1 & 2	B	30.8	39.8	19.6	33.4	8
Total								**259**	

Exp. 17 and 30 were not included in the statistical analysis, because, as split cores, they contemporarily generated three flakes without leaving discernible cores.

The cores show cortical (48.4%), semi-cortical (16.1%) and non-cortical (35.5%) striking platforms (Supplementary file 4: table 1). Their morphological categories (Supplementary file 4: table 2) include plain (51.6%), linear (32.3%), winged (6.5%) and collapsed (9.7%). This latter comprises pieces showing both platform collapse or platform fragment (Driscoll 2010:

128) since it was not possible to observe the impact point because it was covered by macro traces. The striking platforms exhibit flat (54.8%), slightly convex (9.7%), convex (12.9%), slightly sinuous (3.2%), sinuous (6.5%) and irregular (12.9%) delineations (Supplementary file 4: table 3). Impact traces on striking platforms (Supplementary file 4: table 4) include crushing (12.9%) (Figure 6a & b), blunting (22.6%) (Figure 6c), notching (29%) (Figure 6d), whitening (3.2%) (Figure 6e) and the combination of macro traces (19.4%) (Figure 6f & h), while 12.9% do not exhibit impact marks.

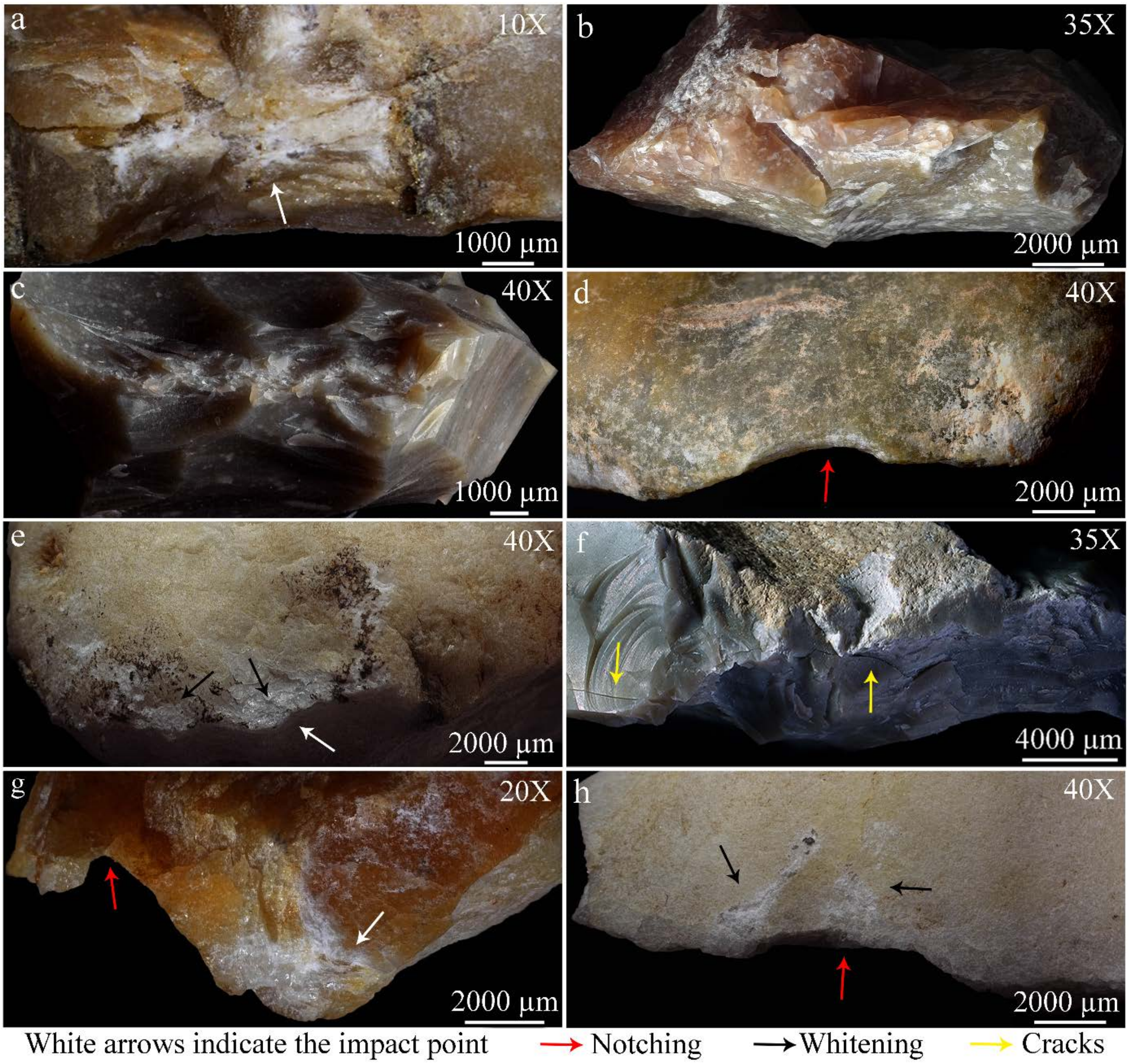

Figure 6. Technical macro traces on striking platforms of experimental chert (b & c), quartz (a, f, & h) and quartzite (d. e, & g) cores: a) crushed impact point; b) crushed striking platform blunted impact point; c) blunted linear striking platform; d) notched impact point; e) whitened impact point; f) crushing and cracks; g) crushing and notching & h) notched and whitened impact point. Black stains in e & h are residues.

The ventral surface of proximal ends display crushing (38.7%) (Figure 7a-c), cascade (16.1%) (Figure 7d), macro scar (12.9%) (Figure 7e), micro scar (3.2%) (Figure (7f), overlapping macro scars (3.2%), the combination of macro traces (9.7%) (Figure 7g & h) and no signs (16.1%) (Supplementary file 4: table 5). The dorsal surface of proximal ends exhibit crushing (16.1%), cascade (9.7%), Hertzian cone (3.2%), whitening (3.2%), macro scar

(3.2%) and overlapping macro scars (3.2%) and the combination of macro traces (6.5%) while the remaining do not exhibit impact traces (54.8) (Supplementary file 4: table 6).

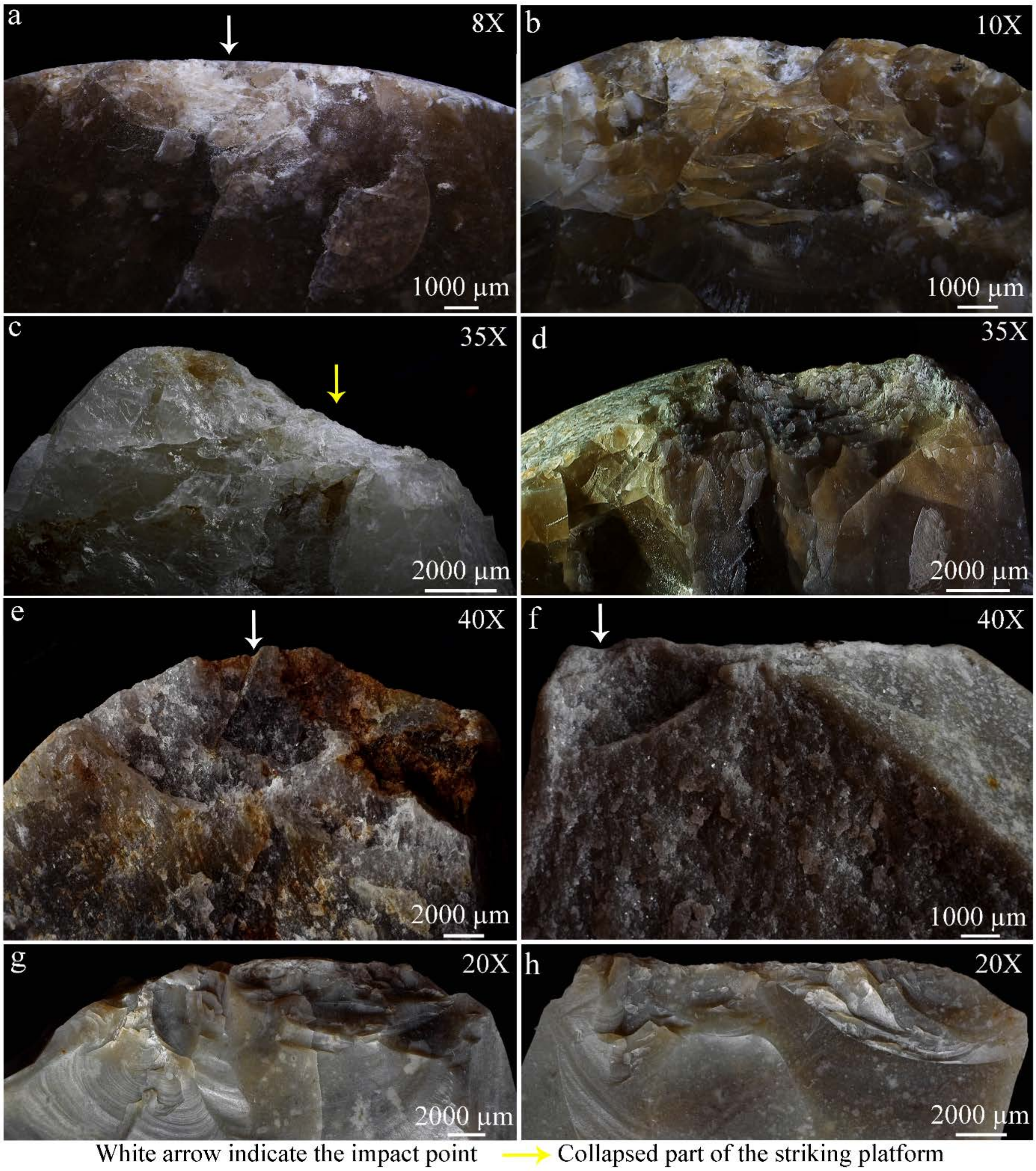

Figure 7. Technical macro traces on the ventral surface of the proximal end of experimental chert (a, b, d, g & h), quartz (c) and quartzite (e & f) cores: a) crushed impact point; b) crushing c) crushing and collapsed striking platform; d) cascade; e) macro scar; f) micro scar; g) crushing and overlapping macro and micro scars and h) overlapping macro and micro scars.

Resting platforms were cortical (64.5%), semi-cortical (3.2%) and non-cortical (32.3%) (Supplementary file 4: table 7). Their morphological categories (Supplementary file 4: table 8) include plain (83.9%), linear (9.6%), winged (3.2%) and collapsed (3.2%) and their delineations (Supplementary file 4: table 9) are flat (54.8%), slightly convex (9.7%), slightly concave (6.5%), concave (3.2%), sinuous (9.7%) and irregular (12.9%). Macro technical traces on the resting platforms (Supplementary file 4: table 10) comprise blunting (6.5%) (Figure 8a), notching (19.4%) (Figure 8b), whitening (9.7%) (Figure 8c & d), incipient Hertzian cone (3.2%) (Figure 8e), double incipient Hertzian cone (3.2%), the combination of macro traces (45%) (Figure 8f-h), while 12.9% do not show macro traces.

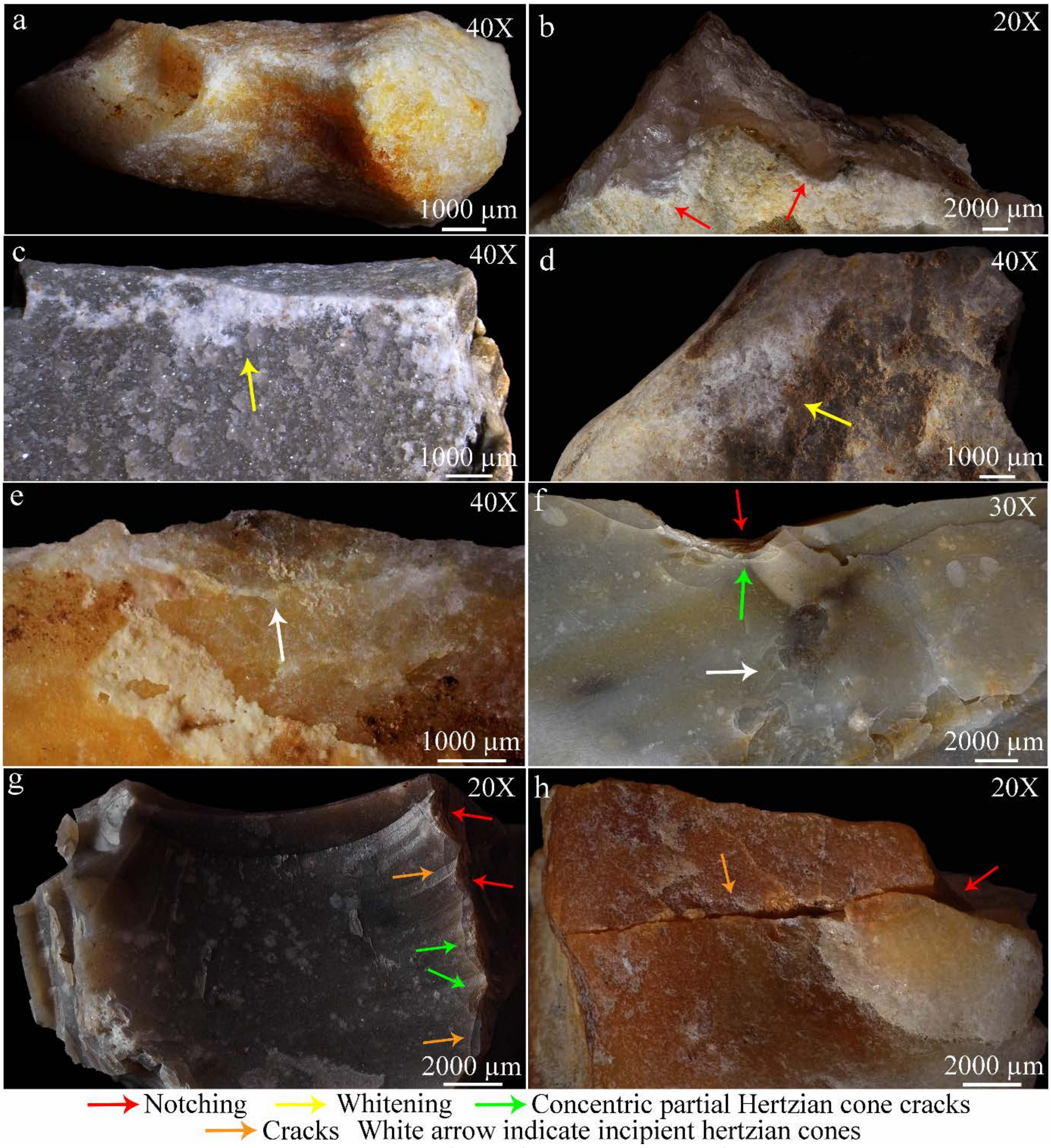

Figure 8. Technical macro traces on resting platforms of experimental chert (f-g), quartz (e) and quartzite (b-d & h) cores: a) blunting; b) notching; c & d) whitening; e) incipient Hertzian cone; f) notching, multiple incipient Hertzian cones and concentric partial Hertzian cone cracks; g) crushing, notching, concentric partial Hertzian cone cracks and cracks; h) notching and crack.

The ventral surface of distal ends exhibit crushing (19.4%), cascade (6.5%), double Hertzian cone (3.2%), macro scar (3.2%), not overlapping macro scars (12.9%), not overlapping micro scars (6.5%), overlapping micro scars (3.2%) and the combination of macro traces (16.1%), while 29% do not show macro traces (Supplementary file 4: table 11). The dorsal surface of distal ends show crushing (6.5%), cascade (3.2%), whitening (3.2%), macro scar (6.4%), not overlapping macro scars (9.7%), not overlapping micro scars (3.2%), overlapping macro scars (3.2%) while 64.5% do not show macro traces (Supplementary file 4: table 12).

The 31 cores show 136 bulbs in total. They are located on the ventral (30.9%), dorsal (8.8%) and lateral (6.6%) surfaces of the striking platforms as well as ventral (28.7%), dorsal (8.8%) and lateral (16.2%) surfaces of the resting platforms (Supplementary file 4: table 13). Bulb (n = 63) and counter-bulb (n = 73) types include flat (21.3%), negative (19.1%), crushed (22.8%), negative crushed (19.6%), sheared (3.7%), double sheared (1.5%), negative spike-shaped (2.2%), dihedral (3.7%), dihedral crushed (2.9%) positive (2.9%) examples (Supplementary file 4: Table 14).

For the scar orientations on cores see Table 9, and see Supplementary file 4: table 15, for the number of scars for each core and their orientations.

Table 9. Scars orientations on experimental cores.

Scars orientations	**Total**
Unidirectional from SP	8
Unidirectional from RP	1
Opposite	17
Orthogonal	5
Total	**31**

In general, only 9.7% of the cores are non-cortical, while 38.7% show cortex <50% and 51.6% >50%. Excluding semi-cortical (n = 9) and non-cortical (n = 1) pebbles and cobbles and three chunks with cortex <50% (Exp. 60.1, 60.2 and 60.3) and three chunks with cortex > 50% (Exp. 47.1, 47.2 and Exp. 49.1) that have been used as cores, 19 cores have been produced from 100% cortical pebbles or cobbles (n = 21). Exp. 17 and 30 are not included in this count because they split into three and four flakes. Of the 19 cores, 42.1% show cortex <50%, while 57.9% show cortex >50%.

3.2. Blanks attributes and macro technical traces results

Flakes (78.8%) represent the majority of the complete blanks produced, followed by bladelets (7.7%) and blades (2.7%). Among the flakes, “orange segments” (5.8%) (Ballin 2021: fig. 4) and “lemon slices” (3.2%) (Bialowarczuk 2015: fig. 3-5) occur (Supplementary file 5: figures 1 & 2). Additionally, there are flake (5%), orange segment and bladelet (1.2%) fragments (1.2%) as well as chunks (2.3%) and shatter (1.2%). Among the 132 blanks from pebbles and cobbles with 100% of cortex, there are primary (30.3%), secondary <50% of cortex (30.3%), secondary >50% of cortex (26.5%) and tertiary (12.9%) examples. The cortex is located on the dorsal surface, butt and counter-butt and one or both of lateral sides. 49.2% of blanks show one sharp edge, 20.5% have two sharp edges, and 30.3% have none. Their morphologies (Supplementary file 5: table 1) are sub-rectangular (34.4%), rectangular (4.8%), sub-square (4%), sub-circular (0.8%), sub-ovate (4.8%), ovate (0.4%), sub-triangular (3.2%) and irregular (47.6%). Average dimensions of complete blanks (n = 231) and fracture types are resumed in Tables 10 & 11.

Table 10. Univariate statistic of dimensions of complete experimental blanks (n = 231), including flakes, blades and bladelets, across lithotypes.

Lithotypes		**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**Weight (gr)**
Chert	N	133	133	133	133
Average length of the	Min	11.0	6.0	2.2	0.4
original pebbles	Max	64.8	70.9	30.2	80.3
78.38±15.33	Mean	30.53	25.64	10.06	9.35
	Stand. dev	10.26	10.92	5.89	12.38
Quartz	N	43	43	43	43
Average length of the	Min	13.2	10.6	3.0	0.7
original pebbles	Max	59.1	61.5	33.2	52.3
52.32±8.6	Mean	33.63	25.02	12.57	13.01
	Stand. dev	10.7	9.77	6.53	11.32
Quartzite	N	55	55	55	55
Average length of the	Min	7.9	5.7	1.6	0.2
original pebbles	Max	45.5	46.3	19.3	30.0
45.7±8.72	Mean	27.81	20.71	8.83	6.95
	Stand. dev	8.36	9.25	4.76	7.47

Table 11. Types of fracture across lithotypes.

Lithotypes	**Chert**	**Quartz**	**Quartzite**	**Total**
Siret	1	6	5	12
Bending	2	2	1	5
Transversal oblique	-	2	-	2
Total	**3**	**10**	**7**	**19**

Butts are cortical (42%), semi-cortical (10.4%), non-cortical (46.4%) and indeterminate (1.2%) (Supplementary file 5: table 2). The morphological categories of the butts (Supplementary file 5: table 3) include plain (42%), linear (30.8%), punctiform (16%), winged (5.6%), collapsed (4.4%) and broken (1.2%). Their profiles (Supplementary file 5: table 4) are flat (34.8%), slightly convex (19.2%), convex (20.4%), slightly concave (1.6%), slightly sinuous (1.2%), sinuous (2.4%), irregular (16.8%), dihedral (2.4%) and indeterminate (1.2%). The impact of the hammerstone on the butt (Supplementary file 5: table 5) often did not leave marks (23.2%), whereas crushing (39.2%), blunting (4.4%), notching (16.4%), incipient Hertzian cone (2.4%), multiple incipient Hertzian cones (0.4%), whitening (2.4%) and the combination of macro traces (10.4%) occur. 1.2% was indeterminate. The ventral surfaces of the proximal ends (Supplementary file 5: table 6) show crushing (45.6%), Hertzian cone (3.6%), multiple Hertzian cones (0.4%), macro scar (8.4%), micro scar (0.4%), not overlapping macro scars (1.6%), overlapping macro scars (0.4%), overlapping micro scars (0.8%) and the combination of macro traces (3.2%), 34.4% do not. 1.2% was indeterminate. Proximal bulbs of percussion (Supplementary file 5: table 7) are flat (32%) (Figure 9a & b), crushed (12%) (Figure 9c), dihedral (6%) (Figure 9d), dihedral crushed (6.8%) (Figure 19e), hinge (8%) (Figure 6f), Hertzian cone (2.8%) (Figure 9g), multiple Hertzian cones (0.4%), negative (6.4%) (Figure 9h) and sheared (4.8%) (Figure 9i). Other examples include positive (2%), positive diffuse (9.2%), negative crushed (5.6%), negative spike-shaped crushed (0.4%). 2.4% do not have bulb and 1.2% was indeterminate. The 59.6% of the dorsal surfaces do not show impact traces (Supplementary file 5: table 8), whilst crushing (23.6%), notching (0.8%), cascade (2.8%), Hertzian cone (1.2%) macro scar (5.6%), micro scar (1.6%) not overlapping macro scars (1.6%), overlapping macro scars (0.8%) and the combination of macro traces (1.2%) occur. The 1.2% was indeterminate.

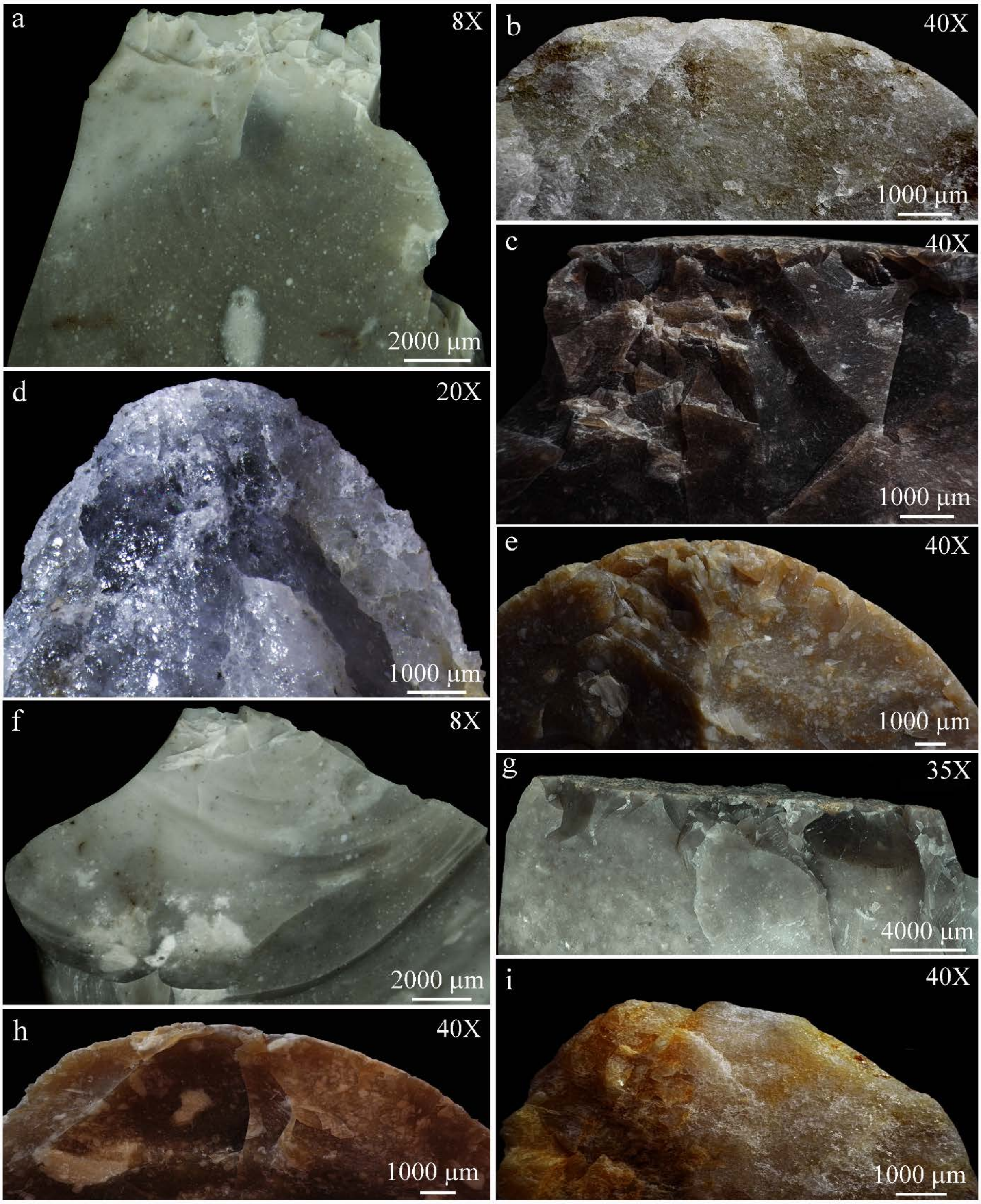

Figure 9. Types of bulb of percussion on experimental chert (a, c & e-h), quartz (i) and quartzite (b & d) blanks: a & b) flat; c) crushed); d) dihedral; e) dihedral crushed; f) hinge; g) Hertzian cone; h) negative and i) sheared.

The blanks profiles (Supplementary file 5: table 9) are straight (30.8%), slightly convex (8%), convex (6.4%), slightly concave (6%), concave (10%), sinuous (22%), twisted (6.4%) and irregular (10.4%). Distal ends (Supplementary file 5: table 10) exhibit axial (52%), feather (26.8%), step (9.2%), hinge (10%) and plunge (2%) terminations. Axial terminations

(Supplementary file 5: table 11) are cortical (58.5%), semi-cortical (9.2%) and non-cortical (32.3%). The axial terminations have plain (66.2%), linear (15.4%), punctiform (10%), winged (4.6%) and collapsed (3.8%) morphological categories (Supplementary file 5: table 12). Their profiles (Supplementary file 5: table 13) are flat (44.6%), slightly convex (13.1%), convex (18.5%), slightly concave (6.2%), concave (1.5%), sinuous (1.5%), dihedral (0.8%) and irregular (13.8%). Crushing (23.1%), blunting (2.3%), notching, (20.8%), incipient Hertzian cone (2.3%), multiple incipient Hertzian cones (1.5%), whitening (5.4%), cracks (0.8%) and the combination of macro traces (22.3%) occur on the counter-butt surfaces, whilst (21.5%) do not show counterstrike signs (Supplementary file 5: table 14). Their ventral surfaces (Supplementary file 5: figure 3 & table 15) show crushing (44.6%), Hertzian cone (1.5%), double Hertzian cone (3.1%), multiple Hertzian cones (0.8%), macro scar (13.8%), micro scar (2.3%) not overlapping macro scars (8.5%), not overlapping micro scars (1,5%), the combination of macro traces (3.8%) and no signs (20%).

78.5% of axial terminations show distal bulb as observed by Kobayashi (1975), Kuijt *et al.* (1995) and Mourre (1996a), while the remaining 21.5% do not. Distal bulb types (Supplementary file 5: table 16) include flat (6.2%), positive (5.4%) (Figure 10a), positive diffuse (0.8%) (Figure 10b), positive prominent (3.1%), double Hertzian cone (0.8%), multiple Hertzian cones (0.8%) (Figure 10c), dihedral (7.7%), dihedral crushed (9.2%) (Figure 10d), negative spike-shaped crushed (1.5%) (Figure 10e), negative (7.7%) (Figure 10f), negative crushed (9.2%) (Figure 10g), crushed (11.5%), sheared (13.8%) (Figure 10h) and double sheared (0.8%). The dorsal surfaces show crushing (23.8%), cascade (2.3%), Hertzian cone (0.8%), macro scar (4.6%), not overlapping macro scars (0.8%), not overlapping micro scars (0.8%), overlapping macro scars (0.8%), cracks (0.8%) the combination of macro traces (1.6%) and no signs (63.8%) (Supplementary file 5: table 17). Table 12 shows from where the blanks were detached.

Flake scar density is low in all the reduction stages with 38% of blanks showing no scars, 35.2% one scar, 14.4% two scars, 5.6% three scars, 2.4% four scars and indeterminate 4.4%. Blanks show the following scar orientations: unidirectional (43.2%), opposite (11.6%), convergent (2%), orthogonal (0.4%), multidirectional (0.4%) and indeterminate (4.4%). See Table 13 for scar orientations of the whole knapped blanks and Table 14 for the bipolar products.

Only one flake, after 20 strikes, was removed from a chert pebble using the hand-held knapping with a quartzitic sandstone without preparing a striking platform (Supplementary file 6: figure 6). A basalt pebble previously failed in its knapping with the hand-held percussion was successfully knapped using the knapping on anvil technique (Supplementary file 6: figure 7).

Table 12. Origin of bipolar and anvil-rested non-bipolar blanks.

	Bipolar			**Anvil-rested non-bipolar**		
	Chert	**Quartz**	**Quartzite**	**Chert**	**Quartz**	**Quartzite**
From striking platform	34	38	24	48	11	15
From resting platform	20	2	12	34	2	10
Total	**54**	**40**	**36**	**82**	**13**	**25**

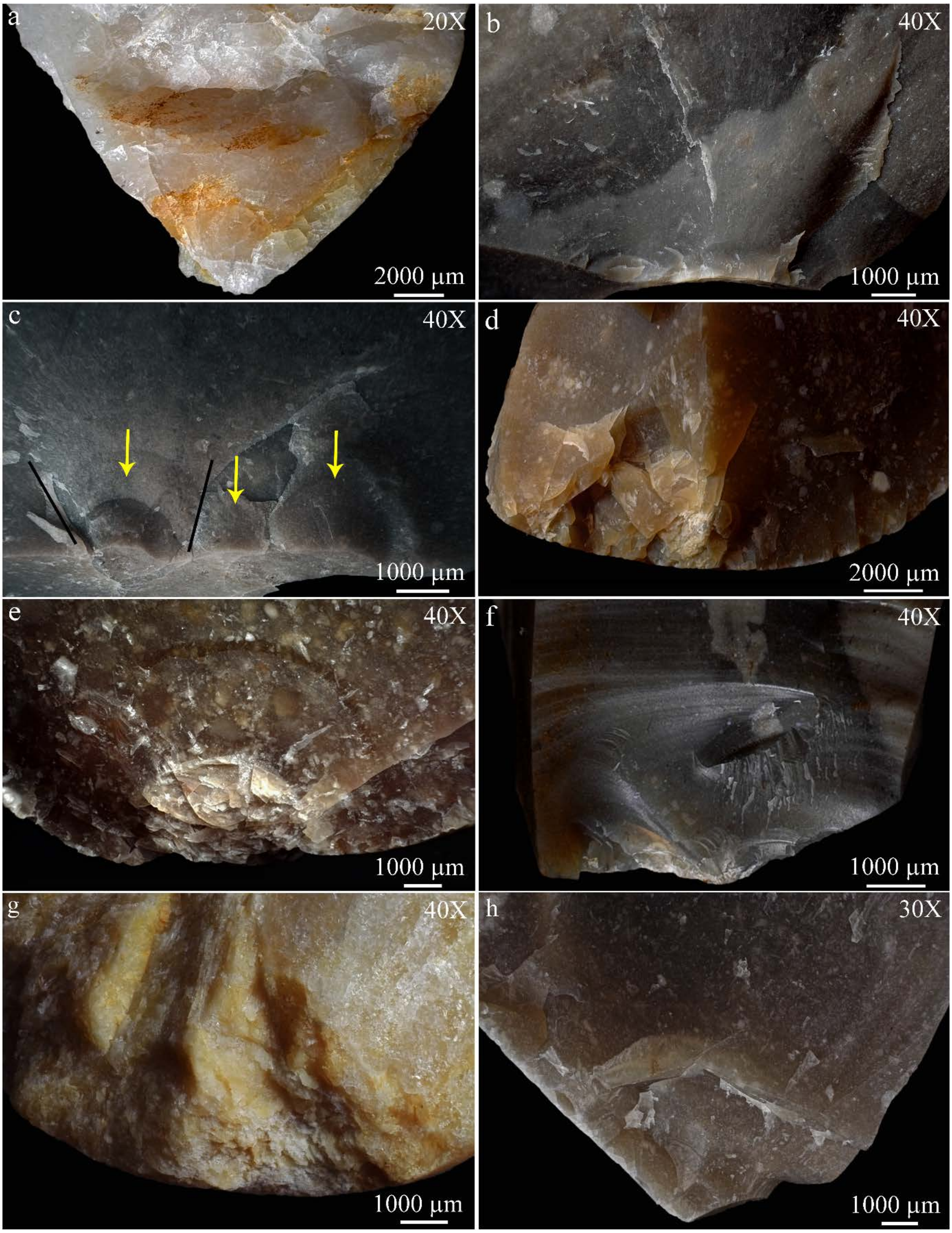

Figure 10. Types of distal bulbs on chert (a, c-f & h) and quartz (b & g) experimental blanks: a) positive; b) positive diffuse; c) multiple Hertzian cones; d) dihedral crushed; e) negative spike-shaped crushed; f) negative, g) negative crushed and h) sheared. Black lines indicate the cone-shaped compression zone of the prominent Hertzian cone, while yellow arrows indicate the position of the Hertzian cones.

Table 13. Blanks scars orientation: SP = striking platform, RP = resting platform and n = number of scars.

Scars orientation	Total
Unidirectional from SP (n = 1)	59
Unidirectional from RP (n = 1)	25
Convergent from SP (n = 1)	1
Convergent from RP (n = 1)	1
Orthogonal (n = 1)	2
Unidirectional from SP (n = 2)	10
Unidirectional from RP (n = 2)	4
Convergent from SP (n = 2)	2
Opposite - from SP (n = 1) and from RP (n = 1)	19
Opposite convergent - from SP (n = 1) and from RP (n = 1)	1
Unidirectional from SP (n = 3)	5
Opposite - from SP (n = 2) and from RP (n = 1)	8
Multidirectional (n = 3)	1
Unidirectional from SP (n = 4)	1
Opposite - from SP (n = 3) and from RP (n = 1)	1
Opposite - from SP (n = 1) and from RP (n = 3)	1
Opposite - from SP (n = 2) and from RP (n = 2)	3
Indeterminate	11
Absent	95
Total	**250**

Table 14. Bipolar blanks scars orientation: SP = striking platform, RP = resting platform and n = number of scars.

Scars orientation	Total
Unidirectional from SP (n = 1)	32
Unidirectional from RP (n = 1)	16
Orthogonal (n = 1)	1
Unidirectional from SP (n = 2)	5
Unidirectional from RP (n = 2)	3
Opposite - from SP (n = 1) and from RP (n = 1)	11
Opposite - from SP (n = 2) and from RP (n = 1)	6
Unidirectional from SP (n = 3)	1
Opposite - from SP (n = 1) and from RP (n = 3)	1
Opposite - from SP (n = 2) and from RP (n = 2)	2
Indeterminate	3
Absent	49
Total	**130**

3.3. Formation of residues and micro technical traces

3.3.1. Residues

During the reduction core, using the knapping on anvil technique, the striking and resting platform undergo multiple contacts with the hammerstone and anvil's surfaces. Each blow may subject the core to compression and traction from the hammerstone and anvil, which leads to the adhesion of residue particles that become compacted over time (Vergés & Ollé 2011). Residues can adhere to both cortical (Figure 11c-d & e-f) and non-cortical Figure 14a-b & g-h) products, primarily due to prolonged percussion. The residues may appear as striated bands or small patches.

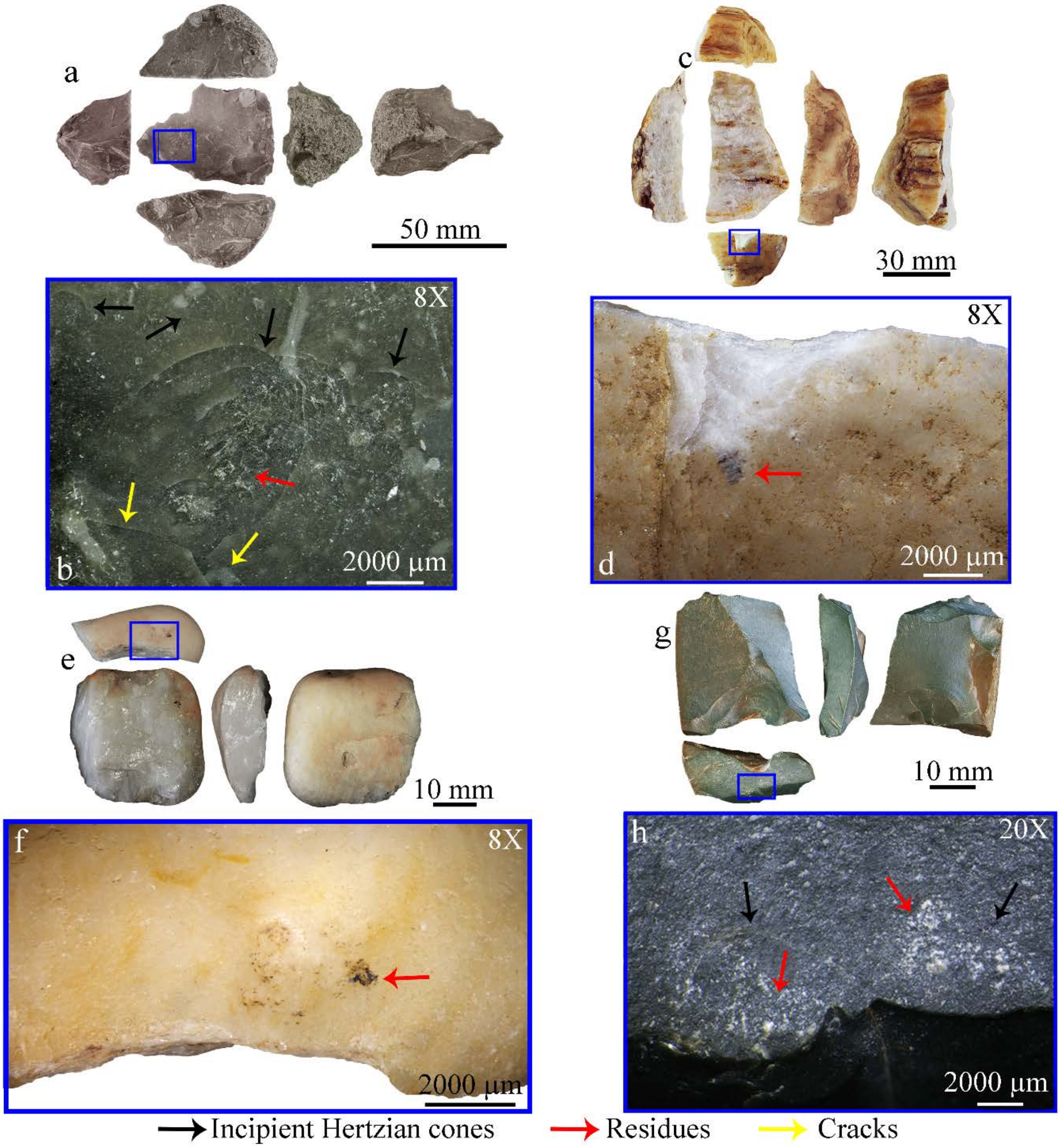

Figure 11. Residues on experimental (a-d) and archaeological (e-h) lithic artefacts: a) chert core; b) non-cortical resting platform showing residues within of incipient Hertzian cones, and cracks; c) quartz flake; d) whitened impact point on cortical butt and residues e) quartz core; f) notched impact point of a cortical striking platform and residue; g) broken flake made from unknown siliceous stone; h) non-cortical butt showing residue within the double incipient Hertzian cone.

Residues can also be found on blanks that are removed with a single blow, as the core may have experienced multiple blows during previous blank removals before it was detached. In this case, residues that were previously adhered to the core surfaces can be dislodged along with the new blank. In our experiment, out of 250 blanks, 19 were obtained with just one blow, and among them, only five displayed residues. See Table 15 for the total number of blows the cores underwent during the experiment and where residue occur and Table 16 for the blanks.

Table 15. Number of blows for each experimental core and residue occurrence on the striking and resting platform.

Core ID	Total blows	Core types		Striking platform residue	Resting platform residue
		Bipolar	Anvil-rested non-bipolar		
Chert					
Exp. 44	21	Y	N	Y	N
Exp. 47.1	3	Y	N	N	Y
Exp. 47.2	17	Y	N	Y	Y
Exp. 49.1	31	Y	N	Y	Y
Exp. 50	28	Y	N	N	Y
Exp. 55	46	Y	N	N	Y
Exp. 59	53	Y	N	N	N
Exp. 60.1	13	Y	N	N	Y
Exp. 60.2	23	Y	N	N	Y
Exp. 60.3	3	Y	N	N	Y
Exp. 61	10	Y	N	Y	Y
Exp. 62	24	N	Y	N	N
Exp. 71	38	Y	N	N	N
Quartz					
Exp. 9	14	Y	N	N	Y
Exp. 13	5	Y	N	N	N
Exp. 14	16	Y	N	Y	Y
Exp. 15	4	Y	N	Y	N
Exp. 20	38	Y	N	N	N
Exp. 31	8	N	Y	Y	N
Exp. 35	20	Y	N	Y	Y
Exp. 67	11	Y	N	Y	N
Quartzite					
Exp. 1	14	Y	N	N	N
Exp. 2	13	Y	N	Y	Y
Exp. 3	3	Y	N	N	Y
Exp. 4	5	Y	N	N	N
Exp. 5	24	N	Y	N	Y
Exp. 6	24	Y	N	Y	N
Exp. 25	2	Y	N	N	N
Exp. 37	15	Y	N	Y	Y
Exp. 42	10	Y	N	Y	Y
Exp. 43	12	Y	N	N	Y
Total		**28**	**3**	**13**	**18**

Table 16. Number of blows for each experimental core, related blanks produced and residue occurrence: * = the total contains a shatter, ** = the total contains one or two chunks, A = include bipolar axial and non-axial blanks and B = anvil-rested non-bipolar blanks.

Core ID	Total blows	Total blanks	Bipolar blanks	Anvil-rested non-bipolar blanks	Butt residue		Counter-butt residue
					A	B	
Chert							
Exp. 44	21	5*	2	2	1	1	-
Exp. 47.1	3	1	1	-	1	-	1
Exp. 47.2	17	10	4	6	2	4	2
Exp. 49.1	31	13	5	8	3	7	4
Exp. 50	28	10**	7	2	1	-	4
Exp. 55	46	24**	14	9	-	1	10
Exp. 59	53	20	5	15	2	3	-
Exp. 60.1	13	6**	2	3	-	-	1
Exp. 60.2	23	10*	3	6	2	-	1
Exp. 60.3	3	3	-	3	-	1	-
Exp. 61	10	8**	2	5	-	-	1
Exp. 62	24	13**	4	7	-	1	2
Exp. 71	38	21	5	16	-	1	1
Quartz							
Exp. 9	14	7	2	5	-	1	-
Exp. 13	5	2	2	-	-	-	-
Exp. 14	16	8	8	-	1	-	4
Exp. 15	4	3	2	1	1	-	1
Exp. 17	2	3	3	-	3	-	3
Exp. 20	38	10	7	3	3	2	2
Exp. 30	6	4	3	1	1	-	2
Exp. 31	8	3	3	-	-	-	-
Exp. 35	20	9	6	3	5	-	4
Exp. 67	11	4	4	-	1	-	2
Quartzite							
Exp. 1	14	4	1	3	-	-	1
Exp. 2	13	9	4	5	-	-	2
Exp. 3	3	2	2	-	-	-	1
Exp. 4	5	4	3	1	-	-	1
Exp. 5	24	10	5	5	2	2	2
Exp. 6	24	10*	6	3	4	-	2
Exp. 25	2	2	2	-	-	-	-
Exp. 37	15	6	5	1	1	-	2
Exp. 42	10	7	4	3	-	1	2
Exp. 43	12	8	4	4	1	-	1
Total		**259***	**130**	**120**	**35**	**25**	**59**

Residues are mostly located next to the impact point on striking platforms (Figure 12a & i) and butts (Figure 12c, e, g & j) or counterstrike on resting platforms (Figure 12b & f) and counter-butt (Figure 12d & h). For other examples of residue adhesion, see Supplementary file 6: figure 1.

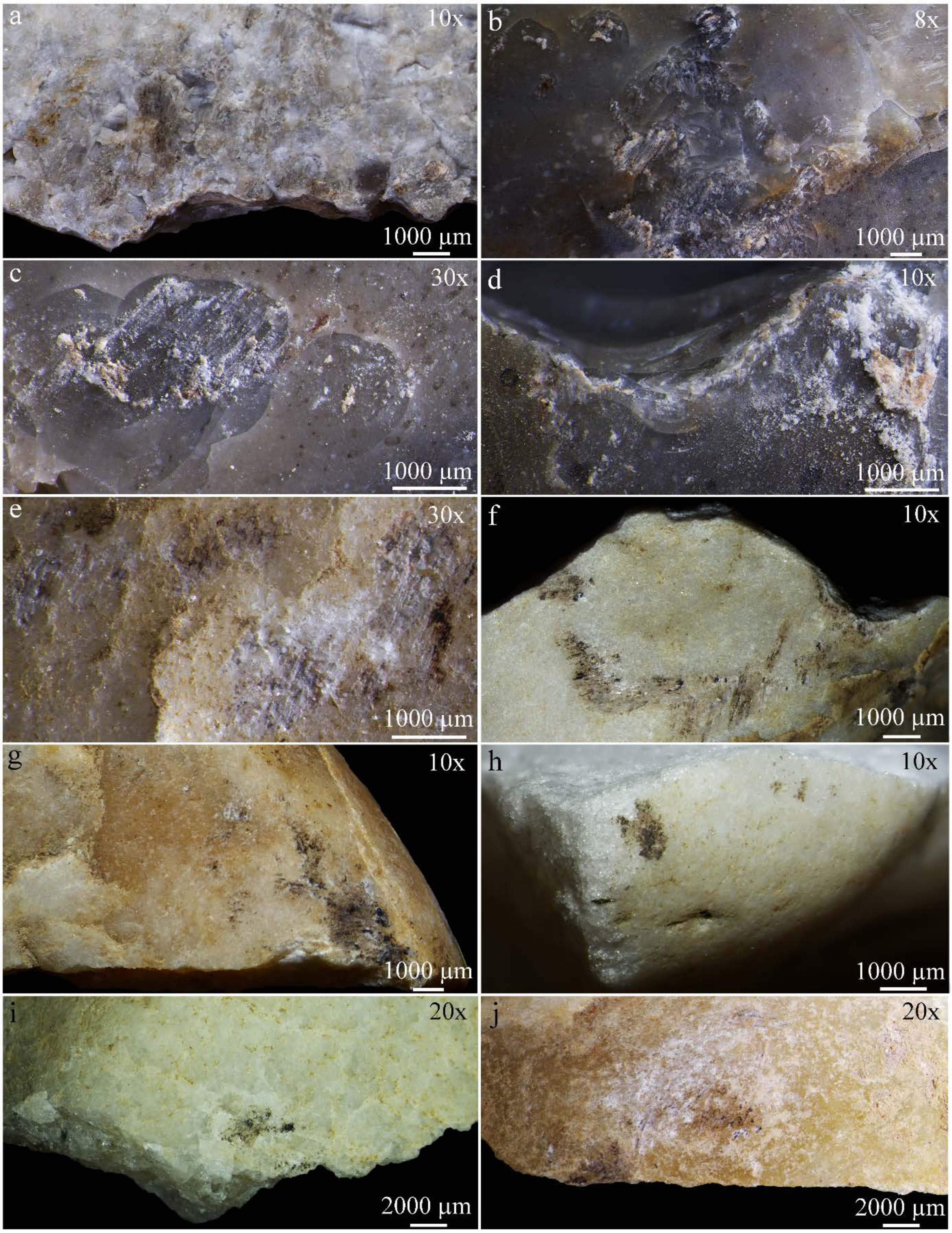

Figure 12. Location of residues detected on experimental chert (a-d), quartz (e-h) and quartzite (i & j) products showing different patterns of adhesion on: a & e) cortical and c) non-cortical striking platforms; c) non-cortical and g) cortical butts; b) non-cortical and f) cortical resting platforms; d) non-cortical and h) cortical counter-butts; i) cortical striking platform and j) cortical butt.

Residues are less frequently recorded during the earlier stages of knapping when the hammerstone and anvil have intact cortical surfaces. However, we observed that with intense use, their surfaces became pitted due to the rupture of their cortex from impacts and counter-strikes. This damage facilitated the adhesion of the pulverised material on the surfaces of the products, even during the earlier stages of knapping. This aspect was not thoroughly explored in our work since it was not one of our primary objectives. A more in-depth investigation is needed to understand its dynamics better.

3.3.2. Striations

Residues may display striations oriented parallel, oblique (Figure 13a & b) or perpendicular (Figure 13c & d) to the transversal axis of a core striking or resting platform and a flake butt or counter-butt and multi-directional oriented parallel striations (Figure 13e & f). Striations aligned to the longitudinal axis (Figure 13g & h) of a core striking or resting platform or flake butt or counter butt are less common, but they occur. Residues rarely appear as small patches (Figure 12h-j). Cracks can also form on compacted residue (Figure 13b).

Typically, residues and striations have been detected on cores and blanks having flat or slightly convex rather than other striking or resting platforms and butt or counter-butt morphological categories and profiles, see Tables 17 and 18.

Table 17. Morphological categories and profiles of striking and resting platforms of experimental cores and occurrence of residues and striations.

Morphological		Striking platform		Resting platform	
Categories	**Profiles**	**Residues**	**Striations**	**Residues**	**Striations**
Plain	Flat	5 out of 9	3 out of 5	10 out of 14	9 out of 10
Plain	Slightly convex	1 out of 2	1 out of 1	3 out of 4	3 out of 3
Plain	Convex	1 out of 1	1 out of 1	-	-
Plain	Slightly concave	-	-	1 out of 2	1 out of 1
Plain	Concave	-	-	0 out of 1	-
Plain	Slightly sinuous	1 out of 1	1 out of 1	-	-
Plain	Sinuous	1 out of 1	1 out of 1	2 out of 3	2 out of 2
Plain	Irregular	0 out of 2	-	1 out of 2	1 out of 1
Linear	Flat	3 out of 7	0 out of 3	0 out of 3	-
Linear	Slightly convex	0 out of 1	-	-	-
Linear	Convex	0 out of 2	-	-	-
Winged	Flat	0 out of 1	-	-	-
Winged	Convex	0 out of 1	-	-	-
Winged	Sinuous	1 out of 1	0 out of 1	-	-
Winged	Irregular	-	-	0 out of 1	-
Collapsed	Irregular	0 out of 2	-	1 out of 1	1 out of 1
Total		**13 out of 31**	**7 out of 13**	**18 out of 31**	**17 out of 18**

Table 18. Morphological categories and profiles of experimental blanks butts and counter-butts and occurrence of residues and striations.

Morphological		Striking platform		Resting platform	
Categories	Profiles	Residues	Striations	Residues	Striations
Plain	Flat	18 out of 36	15 out of 18	33 out of 47	30 out of 33
Plain	Slightly convex	14 out of 31	14 out of 14	5 out of 10	5 out of 5
Plain	Convex	4 out of 14	3 out of 4	3 out of 8	3 out of 3
Plain	Slightly concave	2 out of 3	1 out of 2	3 out of 7	2 out of 3
Plain	Concave	-	-	0 out of 2	-
Plain	Slightly sinuous	1 out of 2	1 out of 1	-	-
Plain	Sinuous	2 out of 3	2 out of 2	0 out of 1	-
Plain	Dihedral	0 out of 1	-	-	-
Plain	Irregular	5 out of 15	4 out of 5	5 out of 11	5 out of 5
Linear	Flat	1 out of 34	1 out of 1	1 out of 5	1 out of 1
Linear	Slightly convex	0 out of 12	-	0 out of 5	-
Linear	Convex	1 out of 12	0 out of 1	1 out of 5	1 out of 1
Linear	Slightly concave	0 out of 1	-	0 out of 1	-
Linear	Slightly sinuous	0 out of 1	-	-	-
Linear	Sinuous	0 out of 3	-	0 out of 1	-
Linear	Irregular	1 out of 14	0 out of 1	1 out of 3	1 out of 1
Winged	Flat	3 out of 8	3 out of 3	3 out of 4	3 out of 3
Winged	Slightly convex	1 out of 2	1 out of 1	-	-
Winged	Convex	0 out of 1	-	0 out of 2	-
Winged	Irregular	0 out of 3	-	-	-
Collapsed	Flat	2 out of 2	2 out of 2	0 out of 1	-
Collapsed	Convex	0 out of 1	-	-	-
Collapsed	Irregular	2 out of 8	2 out of 2	2 out of 4	1 out of 2
Punctiform	Flat	1 out of 7	1 out of 1	1 out of 1	1 out of 1
Punctiform	Slightly convex	1 out of 3	1 out of 1	0 out of 2	-
Punctiform	Convex	1 out of 23	1 out of 1	1 out of 9	1 out of 1
Punctiform	Dihedral	0 out of 5	-	0 out of 1	-
Punctiform	Irregular	0 out of 2	-	-	-
Absent because broken		0 out of 3	-	-	-
Total		**60 out of 250**	**52 out of 60**	**59 out of 130**	**54 out of 59**

The striations are caused by the surface asperities of either an anvil (Figures 13e-h, & 14a-d) or a hammerstone (Figures 13a-d & 14e-h), which plough through the residues. This "ploughed" residue results from friction with the hammerstone or slight movements (traction) occurring on the surface of the anvil (Vergés & Ollé 2011). Both types of interaction may occur multiple times during the reduction process of a core. For additional patterns of striations arrangements, see Supplementary File 6: figures 2 & 3.

3.3.3. Polishing traces

The impact of the hammerstone and the traction with the anvil can lead to the formation of polishing (Figure 15b, d & h) or, in some cases, no polishing at all (Figure 15f) before they are covered by residues (Figure 15a, c, e & g). Sometimes, residues may still be present even after the cleaning procedure, as indicated in a previous study (Byrne *et al.* 2006). Polishing traces become visible only after an extensive cleaning process using 92% hydrogen peroxide, which effectively removes the residues.

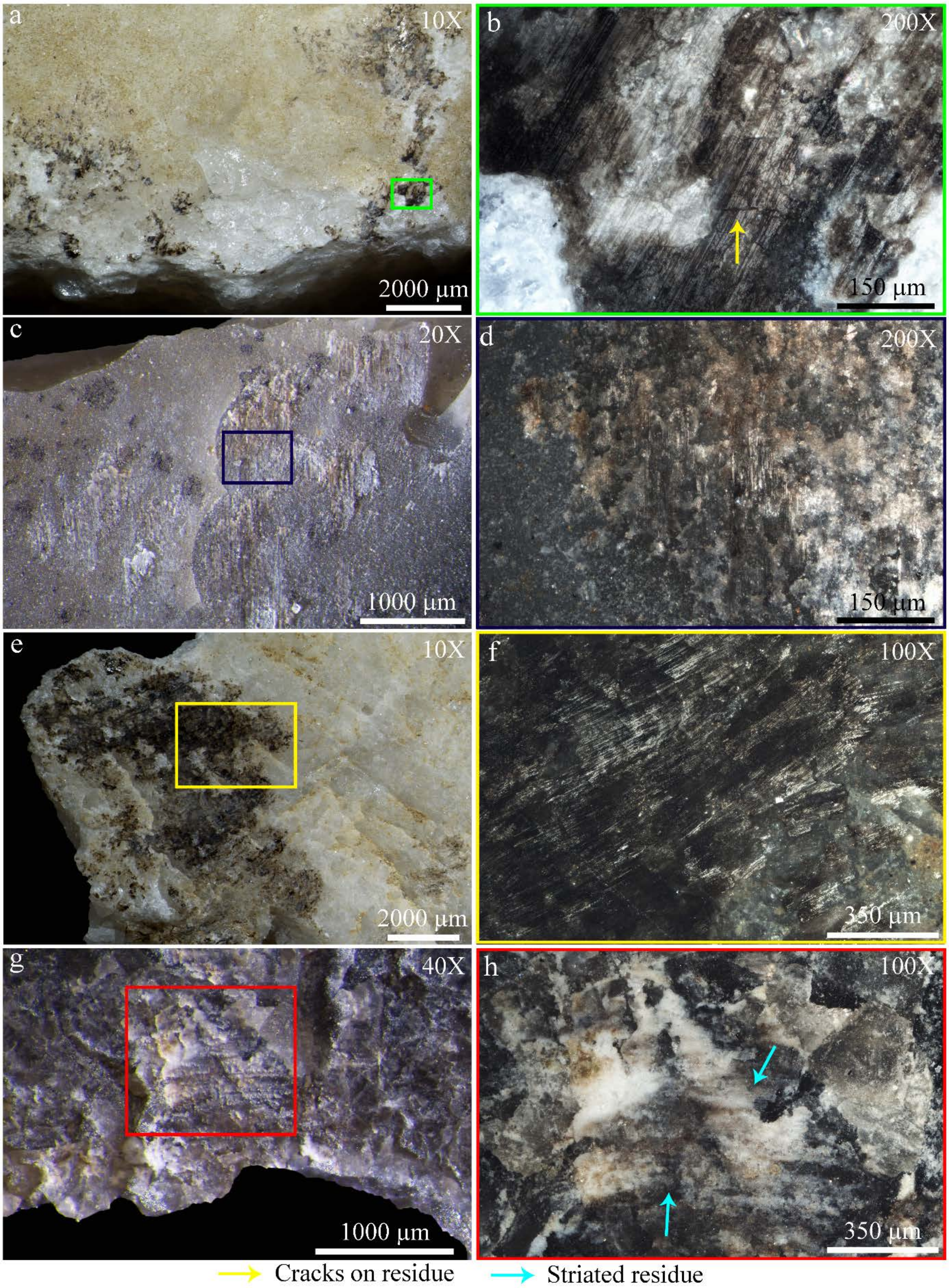

Figure 13. Residues adhered to experimental materials detected with stereomicroscope (a, c, e & g) and metallographic microscope (b, d, f & h): a) quartz cortical striking platform; b) oblique, parallel striations and cracks on residue; c) chert non-cortical butt showing incipient Hertzian cones and parallel striations on residue following the longitudinal axis; d) parallel striations on residue perpendicular to the longitudinal axis; e) quartzite cortical counter-butt; f) multi-directional parallel striations; g) chert cortical counter-butt showing residue ploughed from longitudinal striations and h) residue showing parallel striations following the longitudinal axis.

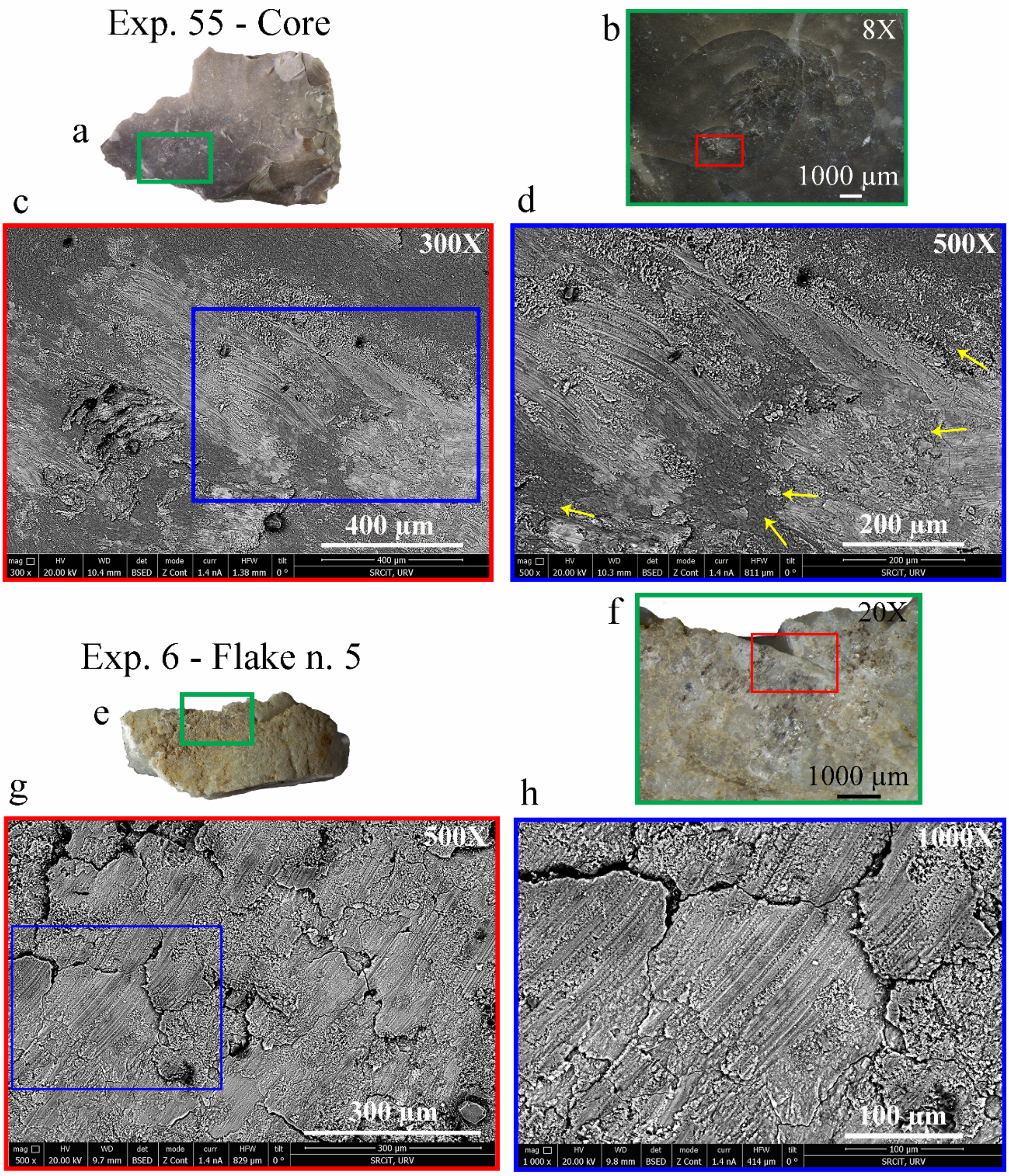

Figure 14. Experimental chert core resting platform (a) and quartzite flake butt (e): b) multiple incipient Hertzian cones and residues; c) previous residues plough by parallel striations developing in several directions, observed with Back-scattered electron detector (BSED); d) detail of e) observed with Back-scattered electron detector (BSED; f) residues; g) previous residues plough by parallel striations developing diagonally to the short axis of the butt, observed with Back-scattered electron detector (BSED) and h) detail of g) observed with Back-scattered electron detector (BSED. Yellow arrows indicate the direction of the striations.

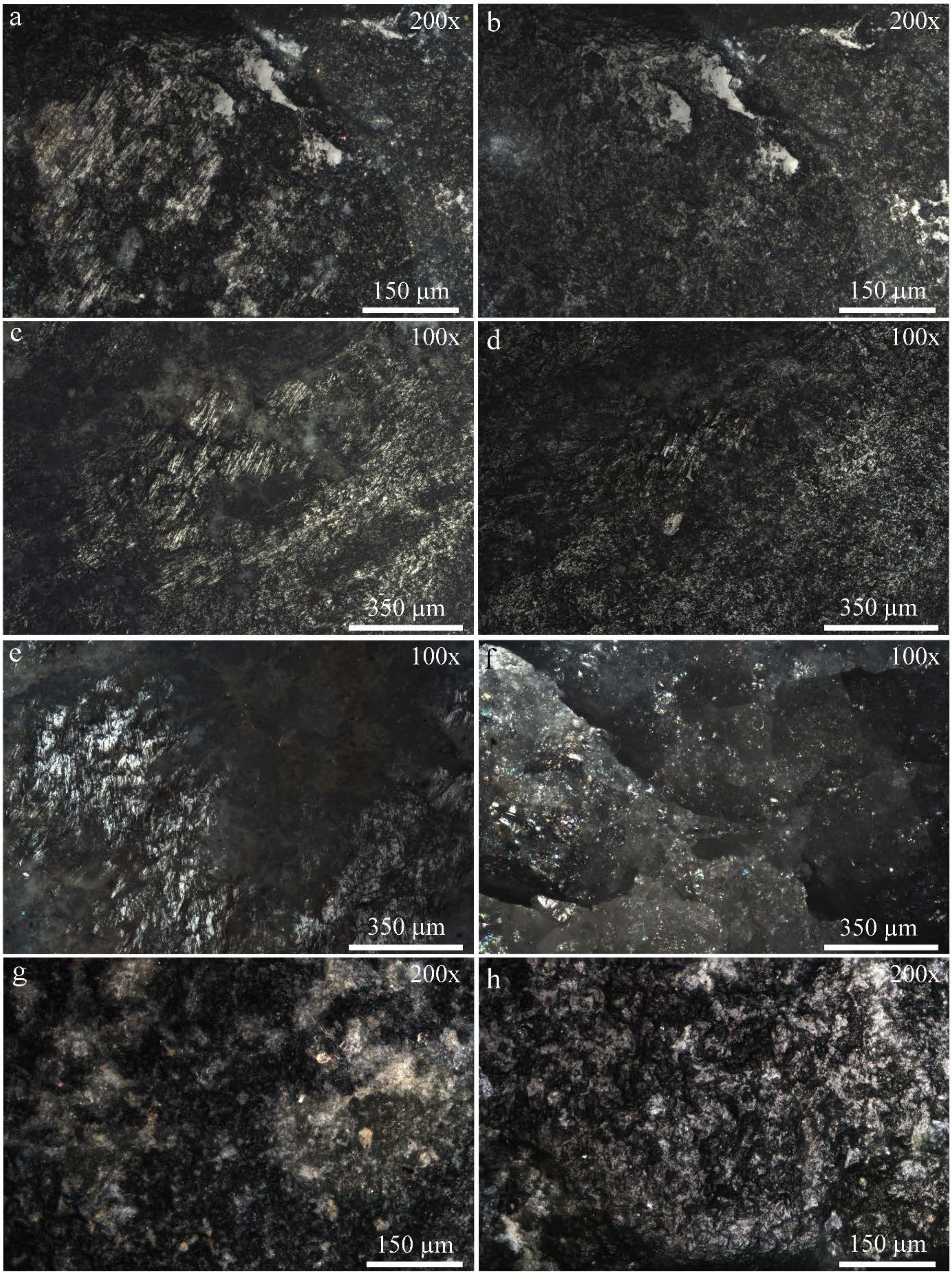

Figure 15. Image showing the same point before (a, c, e & g) and after the cleaning (b, d, f & h) with Hydrogen peroxide at 92% of experimental (a-f) and archaeological (g & h) stone artefacts: a) resting platform of chert core showing striations on residues, incipient Hertzian cone and polishing traces; b) polishing traces, after 60'; c) random striations and residues developed on the resting platform of experimental chert core; d) polishing traces, after 40'; e) random striations and residues developed on cortical butt of quartz flake; f) cleaned cortical butt, after 15'; g) chert flake butt or counter-butts showing residues and h) cleaned surface showing polishing, after 25'.

3.3.4. Characterisation of residues

The Energy-dispersive X-ray spectroscopy (EDS) analysis performed on an experimental quartzite flake (Supplementary file 6: figure 4) identified the presence of silicon (Si), oxygen (O), calcium (Ca), magnesium (Mg), carbon (C), potassium (K) and aluminium (Al). Si and O are the primary components of quartzite, while K and Al are typically present in a minimal amount. Conversely, Mg, Ca, and C can be attributed to the residue left by the dolomite hammerstone used during the knapping process, as these elements overlap in the same spot. A quartz core that was knapped with the same dolomite hammerstone shows the same chemical elements on its striking platform (Supplementary file 6: figure 5a-c). Additionally, Si, O, Al, Mg, Ca, iron (Fe), sodium (Na), C, phosphorus (P), and titanium (Ti) were detected on the butt of a chert flake (Supplementary file 6: figure 5d-f) and the resting platform of a core placed on a quartzitic sandstone anvil. Both specimens were knapped with the same quartzite hammerstone. The EDS analysis of the residues reveals a higher concentration of Al, Mg, and Ca compared to the chert, allowing the interpretation of the residues as quartzite.

The residues found on an archaeological broken flake were located within a double incipient Hertzian cone (Figure 16), which includes Ca, Fe and manganese (Mn), have been interpreted as potentially originating from a granitic rock possibly used as an anvil. This inference is supported by longitudinal striations observed on the residue. Approximately 68% of the macro-lithic assemblage at Mahal Teglinos is made from granite, which comprises grinding, pounding and hammering tools (Rega 2020a: 86-95). The elements composing the residue on the broken flake have been detected among the minerals composing the granite rocks from Mahal Teglinos, such as plagioclase, biotite, pyrite, apatite and ilmenite (Rega 2020a: 362-367). Additionally, the EDS analysis of two distinct types of granite fragments from Mahal Teglinos (Figure 17) confirmed the elements composing the residue on the broken flake for one of them.

4. Discussion

The lithic sample includes "not curated" (Binford 1979) micro-flakes and tools, generally less than 25 mm in length, though there are some rare, larger examples. The collection includes only two blades, two bladelets, and four bladelet fragments. The blanks were made from small, water-worn, rounded, or oval quartz and basalt pebbles as well as chert, chalcedony and agate cobbles. Fourteen cores and eight flakes reused as cores were primarily knapped on an anvil along the vertical longitudinal axis. One core on flake was knapped following the vertical transverse axis. Additionally, four cores were rotated using the vertical longitudinal and transverse axis, while one core was rotated on three sides (anvil-rested, vertical longitudinal and anvil-rested). Only one core, which was knapped using the anvil-assisted method, displays flake removals around its circumference, showcasing a distinct knapping pattern (Supplementary file 1: figure 2d). Furthermore, two small-sized quartz casual cores and a one-platform core appear to have been flaked using the oblique knapping on anvil method (van der Drift 2012). The knapping on anvil was also used to produce tiny flakes measuring less than 15 mm in length, as seen in two chalcedony micro-cores. In a few instances, this knapping technique was further applied to retouch blanks. 11% of the lithics was made using the hand-held technique. The absence of cortex on 77.8% of the hand-held blank butts suggests that the striking platforms of the cores were either prepared or that previous flake scars were used as striking platform (Guardiola *et al.* 2016).

Due to the limited number of lithic artefacts in the analysed sample, we can only provide a preliminary overview of the lithic manufacturing processes at Mahal Teglinos. The knapping on anvil technique was used for flaking chert, quartz, quartzite, agate, chalcedony and basalt.

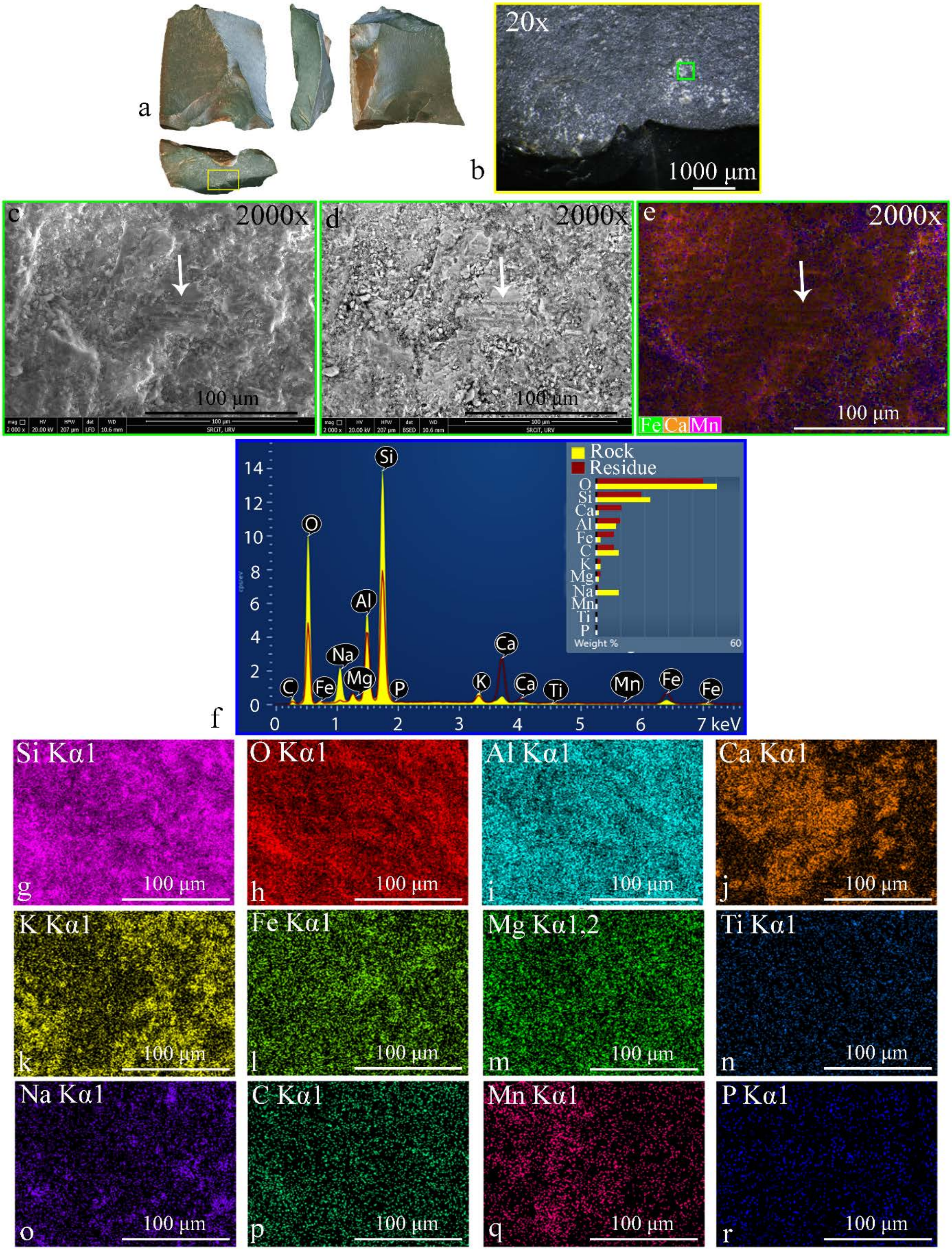

Figure 16. Archaeological broken flake made from siliceous rock: a) siliceous rock broken flake showing residue deposits on the butt/counter-butt; b) close-up of point a) showing the residue deposits; c) SEM image of the residue spot showed in b), marked in green, Large field detector (LFD); d) previous residue observed with Back-scattered electron detector (BSED); e) SEM image showing the superposition of chemical elements identified on the same residue using Energy-dispersive X-ray spectroscopy (EDS); f) EDS spectrogram showing peaks of Si, O, Al, Ca, K, Fe, Mg, Ti, Na, C, Mn and P; g to q) spectra maps of all peaks identified. White arrows indicate the striations.

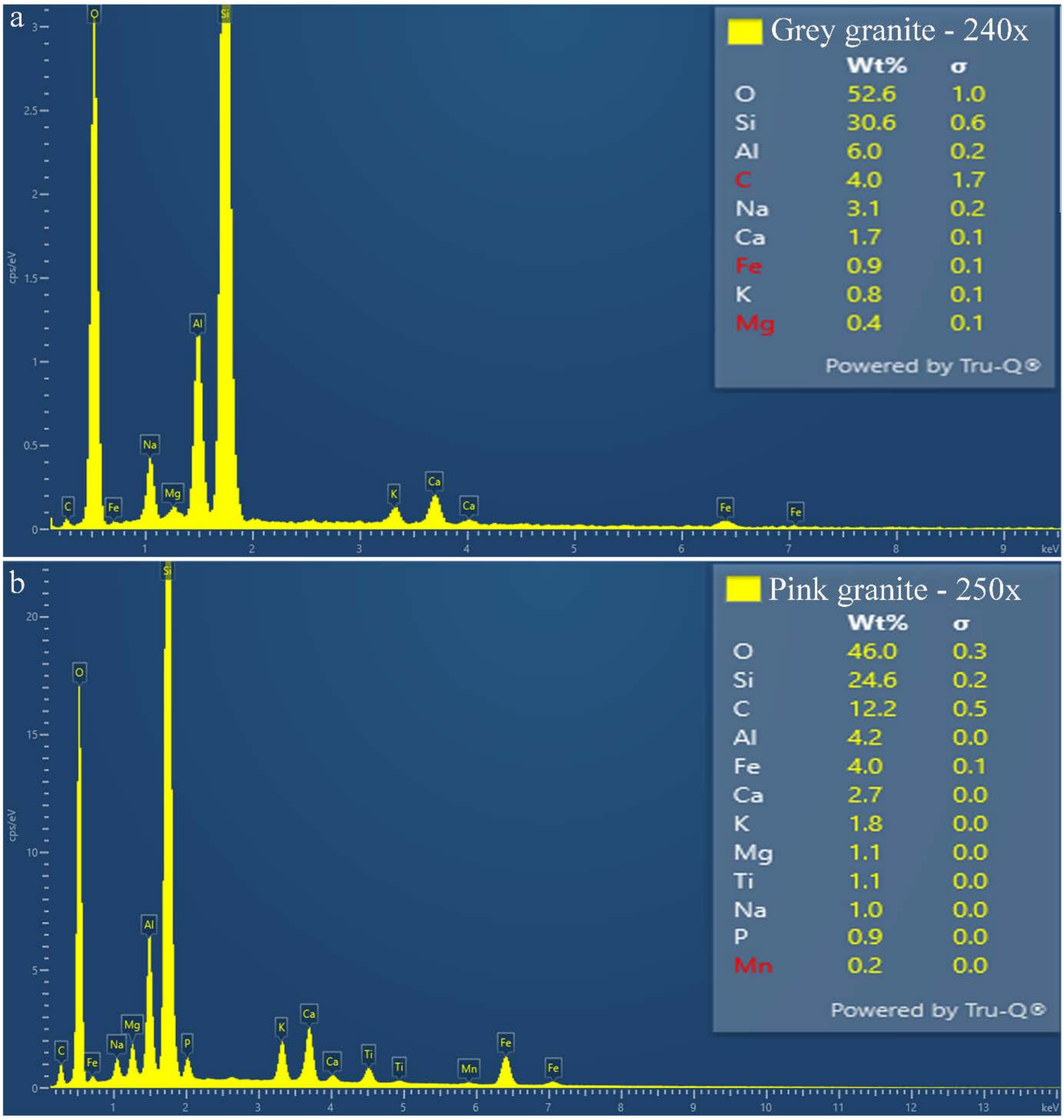

Figure 17. Energy-dispersive X-ray spectroscopy (EDS) analyses of two granite fragments from Mahal Teglinos: a) grey granite and b) pink granite, which show the elements composing the residue identified on the archaeological broken flake.

In contrast, the hand-held technique appears primarily associated with chert, likely due to the size of the pebbles.

Studies indicate that the knapping on anvil technique significantly enhances the efficiency of the transmission of energy and reduction processes, especially when dealing with small or poor-quality raw materials (Andrefsky 1994; Flenniken 1980; Prous & Alonso 1990; Tallavaara *et al.* 2010; Yang *et al.* 2016). However, the selection of pebbles or small cobbles and specific lithotypes may reflect cultural decisions rather than natural constraints (Boëda *et al.* 2014; Gallotti *et al.* 2020; Marciani *et al.* 2020; Marks *et al.* 1987).

Quartz pebbles originate from the eroded granitoid formations near Kassala (Geological Research Authority of the Sudan (GRAS) 2004; Costanzo *et al.* 2021) and occasionally occur in the Gash River's sandy riverbed near Mahal Teglinos. Chalcedony and agate nodules are commonly found in the sites of the western portion of the plain separating the Gash and

Atbara rivers and originate from Cainozoic basalt outcrops eroded by the Atbara River south of Khashm el Girba (Abbate *et al.* 2010). In contrast, the larger chert cobbles are not local. Potential sources of chert may include the Ethiopian Plateau to the southeast, which is approximately a three-day walking distance along the Takazze River. The Takazze River is a tributary of the Atbara River, and it could transport eroded chert pebbles and cobbles from the Ethiopian Plateau. Other potential chert sources are the Hudi Formation to the north (Abbate *et al.* 2010; Bussert *et al.* 2018; GRAS 2004) and the Shendi Reach Formation to the northwest (Babkir *et al.* 2023*).* In the southwest, another potential source is the Khashm el Girba area, where the gravel bars of the Atbara River contain pebbles and cobbles of chert, agate, quartz, quartzite, greenstone, and volcanic rock (Marks *et al.* 1987).

Our hypothesis, based on the material analysed so far, is that the use of knapping on the anvil was a cultural decision made by the Gash Group knappers rather than a natural constraint for producing small blanks and tools from small pebbles and cobbles of various lithotypes, particularly quartz and chalcedony. The lithic artefacts created using this knapping technique likely fulfilled specific objectives within their technological system and agro-pastoral economy. The case of six chert and two quartz cores on flakes also attests to the use of the knapping on anvil technique to recycle blanks (Barsky *et al.* 2015; Zaidner 2013). The remaining three exhausted chert cores and a two-platform core are non-cortical or semi-cortical, with cortex less than <50%, indicating that they were in an advanced stage of reduction or were likely reused chunks. In our experiment, when 100% of the cortical pebbles were reduced, 86.7% of the blanks and all the cores retained some cortex. Other experiments have also shown a higher percentage of cortex on knapped on anvil products when employing small cobbles or nodules (Ahler 1989; Kuijt *et al.* 1995). Furthermore, there is no evidence that the hand-held percussion was applied to these cores before flaking with the knapping on anvil technique. In contrast, only two quartz flakes were reused as cores, while none of the quartz cores could be knapped using hand-held percussion due to their small size.

In the surrounding regions of Mahal Teglinos, hand-held products and those derived from the knapping on an anvil technique were identified at several sites. Analysis of the lithic assemblages from Mesolithic and Neolithic sites near the Atabara River to the northeast of Khashm el Girba revealed that the knapping on anvil technique increased when the blade production decreased at KG 68. This knapping technique was used for producing agate and quartz blanks and tools, unlike at KG 15/16, KG 73 and KG 74, where chert was the predominant lithotype, followed by agate (Marks 1987; Marks *et al.* 1987). Other Neolithic sites in the Butana region yielded knapped on anvil lithics in varying quantities, ranging from the least to the most represented (Mbutu 1991).

Investigations at the Kokan rock shelter, located in Agordat, Eritrea, provided a chronological framework spanning the Middle and Classic Gash Group (2300-1700 BCE) to the Pre-Axumite period (7th-3rd Centuries BCE). The most flaked lithotypes were quartz and basalt, followed by obsidian and chert. Both hand-held and knapping on anvil techniques were identified, with the latter accounting for 12% of the cores (Brandt *et al.* 2008). In the Aksum conurbation, lithic assemblages from Pre-Aksumite and Aksumite sites include obsidian cores and blanks showing evidence of knapping on anvil along with chert, quartz hand-held products (Phillipson 2009).

Macro-technical traces and attributes of products derived from the knapping on anvil technique are easier to recognise in chert (de la Peña 2015a; 2015b) than in quartz (Driscoll 2011; de Lombera Hermida 2009; Mourre 1996b; Tallavaara *et al.* 2010) and quartzite (Byrne *et al.* 2015; Proffitt & de la Torre 2014). It depends on the proprieties of these rocks (Cotterell & Kamminga 1990: 129; Driscoll 2010: 5-8; de Lombera Hermida 2009; Luedtke 1979; Mourre 1996b, Seong 2004; Will 2021). Quartz and quartzite are not a homogenous raw material and tend to break unintentionally due to their low elasticity, internal flaws, and crystalline surfaces (de Lombera Hermida 2009; Tallavaara *et al.* 2010). Depending on the internal flaws, chert nodules can also lead to unpredictably flaking (Ma *et al.* 2020).

Hayden (1980) noted that identifying the knapping on anvil blanks relies on several diagnostic patterns, not all of which need to be present. In our experiment, isolated technical macro traces or their combination developed on cores and blanks in different positions, confirming the result of Hayden's experiment. For these reasons, it is better to create an experimental programme to record with a more conservative observation as many variables as possible involved in the formation of macro and micro technical traces as well as the adhering of residues on butts or counter-butts and striking or resting platforms. In other experiments dealing with the interpretation of knapping on anvil and hand-held products, a more conservative observation resulted in a more precise identification of such products (Byrne *et al.* 2015; Proffitt & de la Torre 2014). These variables include the position and the shape of the core and the profile of the striking and resting platforms (Boëda *et al.* 2014; Ollé & Vergès 2011) and anvil (Arrighi *et al.* 2020; Jeske 1992). These factors increase the contact points during impact and affect the control of transmitted energy. Further variables to consider are the lithotypes, hardness and mass of the hammerstone (Byrne *et al.* 2006; Crabtree 1967; van der Drift 2009; Proffitt *et al.* 2016; Rots 2010a; Yeşilova *et al.* 2024), anvil (Arrighi *et al.* 2020; Roda Gilabert *et al.* 2012) and core (van der Drift 2009). Furthermore, knapping skill may influence the final products in both knapping on anvil and hend-held techniques (Byrne *et al.* 2015; Proffitt *et al.* 2016 and references cited therein; Yeşilova *et al.* 2024).

A chert core (Exp. 55), produced by knapping in the anvil-assisted position from one half of a split cobble (Supplementary file 3: figure 2e), displayed a carinated morphology with denticulated delineations (Figure 11a), resembling the so-called Clactonian notches, which are essentially the negative of the removed flakes. Other experiments have yielded similar results (Crovetto *et al.* 1994; Van der Drift 2009; Vergès & Ollé 2011; Zaidner 2014). This type of core is absent from archaeological specimens. The other experimental cores share features, such as shapes and technical macro traces, as recorded in other studies (Grimaldi *et al.* 2007; Sánchez-Yustos *et al.* 2017; Zaidner 2014).

In our experiment, excluding the 130 axial blanks and employing a conservative approach for analysing the specimens, only one flake exhibiting a hinged bulb and a step termination could be misinterpreted as having been knapped using a hand-held percussion technique out of 120 anvil-rested blanks. The remaining artefacts displayed at least one macro or micro technical trace resulting from the knapping on anvil technique. Although 40 of these blanks exhibited various butt morphologies, including plain, slightly convex, convex, irregular, or slightly concave, as well as non-axial terminations that could also arise from hand-held percussion, their association with technical traces from the anvil technique confirms they are indeed anvil-knapped products. Of the 130 axial blanks, four and one of the 120 anvil-rested blanks exhibited one or two prominent bulbs on the ventral surface of both the distal and proximal ends. The four axial blanks come from Exp. 55, which was positioned in the anvil-rested state. It featured a convex striking platform and a flat resting platform. A prominent bulb is characteristic of the hand-held knapping method, in contrast to the diffuse bulb, which is associated with knapping on an anvil (Supplementary file 2: figure 3), particularly employing the oblique method (Van der Drift 2012). It is essential to identify macro or micro technical traces from knapping on an anvil, along with the presence of prominent bulbs on blanks, to prevent misinterpretation of the knapping technique. All archaeological blanks with a prominent bulb have been categorised as hand-held products because they did not display macro technical traces typical of the knapping on anvil technique. Conversely, none of the archaeological knapped on anvil blanks showcased this type of bulb of percussion. This aspect necessitates further investigation, as prominent bulbs were not anticipated in blanks resulting from the anvil knapping technique.

Notching and whitening (Driscoll 2010: 146) observed on some archaeological and experimental cores are not technical macro traces exclusive to the knapping on anvil technique. While they can also result from hand-held knapping, the presence of these impact or counter-strike marks on pebbles and small cobbles suggests that they were likely cores knapped using the knapping on anvil technique. It is established from previous studies that knapping waterworn round or oval pebbles and small cobbles using a hand-held technique is difficult, if not impossible, due to the absence of a natural striking plane (Andrefsky 1994; van der Drift 2009; 2012; Flenniken 1980: 51-52; Prous & Alonso 1990). For instance, see our negative attempts at hand-held knapping of chert, quartzite and basalt small cobbles less than 100 mm in length (Supplementary file 6: figures 6 & 7). Therefore, the presence of these macro traces would suggest a likely connection to the anvil knapping technique.

Residues have only been detected on a broken flake featuring plain morphology and a flat profile of the butt or counter-butt, along with a core exhibiting plain morphology and a slightly convex profile of the striking platform. The lower percentage of residues found on archaeological materials compared to experimental ones may depend on several factors (Cnuts & Roots 2024; Touzé & Rots 2025), including the prior cleaning conducted before this study. The residues observed on the broken flake display parallel striations that follow the longitudinal axis of the butt or counter-butt. They are located within a double incipient Hertzian cone, and are indeed manufacturing residues rather than resulting from subsequent contamination. This pattern of striated residue may result from the traction of the anvil, as observed on three experimental flakes removed from the counterstrike (Supplementary file 6: figure 8). None of the experimental blanks detached by the impact with the hammerstone shows the striated residue pattern identified on the archaeological specimen. In contrast, the blanks detached by the impact with the hammerstone may exhibit clusters of parallel striations that abruptly change direction, as previously demonstrated by Vergès & Ollé (2011), or striations perpendicular to the longitudinal axis of the butt and counter-butt, or striking and resting platforms.

In distinguishing between products created using hand-held and knapping on anvil techniques, which display macro technical traces that can stem from both methods, such as plain morphology and cortical or non-cortical flat or slightly convex profiles of the butt, light crushing, prominent and hinged bulbs, the distribution pattern of residues and striations is an important factor to consider, if they occur. Our experimental hand-held flakes exhibit residues ploughed by oblique striations or striations following the longitudinal axis of the non-cortical butts. In 90% of cases, these striated residues are located within the incipient Hertzian cone (Supplementary file 6: figure 9), with very few found outside this area, as also demonstrated in other experiments on producing hand-held chert blades (Touzé & Rots 2025) and blanks using hammerstones from various lithotypes (Rots 2010a). Furthermore, the non-cortical butts predominantly show a single impact point, with occasional double impact points. In contrast, detaching a blank using the knapping on anvil technique typically requires multiple strikes, as observed in our experiment and supported by earlier research (Jeske 1992; Kuijt *et al.* 1995). In instances of cortical butts, the incipient Hertzian cones do not occur. The knapping on anvil increases variability in both technical macro (Hayden 1980) and micro traces (Vergès & Ollé 2011) and may result in the deposition of residues in different areas of the blank's butt and counter-butt or a core's striking and resting platforms. However, we noted that more than one blank can be detached simultaneously. In such cases, only the blank that experiences significant impacts with the hammerstone and rebound from the anvil is likely to show technical micro-traces and residues. In contrast, the others do not, making their interpretation difficult if none of the technical attributes are present.

Similar patterns of residues and striations can be observed on blanks that have been tangentially knapped (Ibañez *et al.* 1990; Rots 2010a; 2010b: 249 & 251-252) or retouched using either hand-held percussion or a stone as an anvil (Byrne *et al.* 2006; Fasser *et al.* 2024; Ibañez *et al.* 1990; Keeley 1980: 20; Mansur-Franchomme 1986: 214-215; Rots 2010b: 43-44 & 248-253). However, for tangential retouch, the residues and striations are distinct from those produced by the anvil knapping technique. This distinction arises from their location on either the ventral or dorsal surfaces of the blank's edges, as well as the lighter development of residues and the rarity of incipient Hertzian cones (Fasser *et al.* 2024; Rots 2010b: 43-44). In contrast, products that have been knapped on an anvil may exhibit flaking residues and striations on the butt or counter-butt, along with striking or resting platforms. For a comparison of the striated residues produced by knapping on anvil and hand-held techniques, refer to Supplementary file 6: figures 2-3 & 9-10.

5. Conclusions

Our research provides diagnostic macro and micro technical traces derived from the knapping on anvil technique, offering new insights for identifying products created through the exploitation of pebbles and small cobbles. The complementary approach we propose for studying cores and blanks may assist in recognising them as products of knapping on an anvil technique, particularly in lithic assemblages that comprise products from different knapping techniques. This approach is particularly advantageous for cores, and for blanks that may display features similar to those of hand-held products.

Additionally, our study provides guidance on where to search for residues and striations, enabling researchers to apply this methodology more efficiently and avoid wasting time selecting materials for analysis. Since this preliminary study was conducted on a small set of a lithic assemblage that had already been analysed and cleaned, we plan to extend this analysis to new materials from Mahal Teglinos. This will assist us in reconstructing the steps of the *chaîne opératoire*, from selecting the raw materials used as hammerstones and anvils to the utilisation of the stone artefacts.

The production of blanks from pebbles and small cobbles using the knapping on anvil technique at Mahal Teglinos and other sites in Eastern Sudan may have resulted from the economic changes occurring after the Neolithic period, particularly with the adoption of an agro-pastoral system by the Gash Group people.

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Data accessibility statement

The authors confirm that all the data supporting the findings of this study are available within the paper and supplementary materials

List of Supplementary files

Supplementary file 1
“Capra et al. - Supplementary file 1 - archaeological - cores.docx”
Archaeological materials - Attributes and macro-traces of cores

Supplementary file 2
“Capra et al. - Supplementary file 2 - archaeological - blanks.docx”
Archaeological materials - Attributes and macro-traces of blanks

Supplementary file 3
“Capra et al. - Supplementary file 3 - experimental - pebbles and cobbles.docx”
Experimental materials - Pebbles and cobbles

Supplementary file 4
“Capra et al. - Supplementary file 4 - experimental - cores.docx”
Experimental materials - Attributes and macro-traces of cores

Supplementary file 5
“Capra et al. - Supplementary file 5 - experimental - blanks.docx”
Experimental materials - Attributes and macro-traces of blanks

Supplementary file 6
“Capra et al. - Supplementary file 6 - experimental - residues and micro technical.docx”
Experimental materials - Residues and micro technical traces of cores and blanks

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Esplorare la produzione di strumenti litici a Mahal Teglinos (Sudan orientale): un approccio sperimentale per la caratterizzazione dei residui, delle macro e micro tracce derivate dalla scheggiatura su incudine di ciottoli e ciottoloni di quarzo, quarzite e selce

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Sommario:

Nonostante l'esistenza di un'intensa ricerca focalizzata sulla caratterizzazione delle macro tracce derivate dall'uso della tecnica di scheggiatura su incudine, poca attenzione è stata dedicata all'individuazione delle micro tracce tecniche e dei residui su schegge e nuclei prodotti per mezzo di questa tecnica di scheggiatura. Le tracce macro tecniche derivate dalla tecnica di scheggiatura su incudine sono state individuate su manufatti in pietra provenienti dall'assemblaggio litico del Gruppo Gash (metà III - inizio II millennio a.C.) a Mahal Teglinos (K1), situato nella moderna regione di Kassala, nel Sudan orientale. Un programma sperimentale è stato sviluppato per localizzare i residui e le macro e micro tracce di produzione di questa tecnica di scheggiatura, utilizzando ciottoli e piccoli ciottoloni di quarzo, quarzite e selce per creare una collezione di riferimento per l'interpretazione del materiale archeologico. La metodologia adottata per questo studio prevedeva l'uso combinato di diversi microscopi per l'analisi delle tracce e dei residui. I microscopi digitali stereo e 3D sono stati utilizzati per caratterizzare le tracce macro tecniche e individuare eventuali residui. La composizione chimica elementare dei residui è stata caratterizzata attraverso la microscopia elettronica a scansione (SEM) utilizzando raggi X a dispersione di energia (EDS) e mappe di elementi. L'associazione di macro e micro tracce (evidenze di politura e striature) identificate sui materiali sperimentali ha permesso di confrontare e individuare tracce tecniche simili su alcuni materiali archeologici, in quanto esistono casi in cui simili macro tracce possono derivare dalla scheggiatura a percussione diretta. Il nostro esperimento ha dimostrato che le macro tracce sono presenti su quasi tutte le repliche di manufatti litici, mentre i residui si sviluppano più facilmente su manufatti litici con caratteristiche specifiche del tallone e del tallone opposto delle schegge e sul piano di percussione e la superficie in contatto con l'incudine dei nuclei. Le micro tracce tecniche confermano che le schegge e i nuclei sono stati prodotti con la tecnica di scheggiatura su incudine quando le macro tracce caratteristiche di questa tecnica di scheggiatura sono presenti sui manufatti litici di un assemblaggio, mentre i residui indicano la litologia del percussore e dell'incudine utilizzate.

Keywords: tecnica di scheggiatura su incudine; macro e micro tracce tecniche; analisi dei residui; microscopia elettronica a scansione; spettroscopia a raggi X a dispersione di energia