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Stones in the toolkit

Contribution of use-wear and residues analysis to the identification of Copper and Bronze Age metal object production in Europe between the 3rd and 1st millennium BC

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Abstract: The emergence and development of copper and bronze metallurgies, but also of those of precious metals such as gold and silver, are major issues in addressing the cultural and economic dynamics of prehistoric Europe. However, since research has focused on typologies and distribution of metal objects, the documentation on the structures of ore extraction and metal production workshops remains disparate, and only partially enlightens the stages of production.

The identification of the stone tools involved in these technical processes makes it possible to partially fill this gap in continental Europe. Thus, recent work in use-wear and residue analysis (e.g. XRF, SEM-EDX) on different categories of stone tools (picks, crushers, grinders, casting moulds, anvils, abraders, hammers, whetstones, etc.) have made it possible to specify the technical processes used for extracting ores, transforming them into metal, shaping metal objects and maintaining them.

This paper discusses the contribution of functional analyses to the identification of these tools, and of the contexts of metal production during Metal Ages. The presence of such tools in settlements, in workshops, as well as in particular funerary contexts, allows us to better understand the organisation of production and the degree of specialisation of metalworkers within the societies of the 3rd to 1st millennium BC.
Keywords: Metallurgy; Lithic tools; Bronze Age; Use-wear analysis; XRF; SEM-EDX.

Résumé : L'émergence et le développement des métallurgies du cuivre et du bronze, mais aussi des métaux précieux comme l'or et l'argent, constituent des questions majeures pour aborder les dynamiques culturelles et économiques de l'Europe préhistorique récente. Cependant, si les recherches se sont concentrées sur les typologies et la distribution des objets métalliques, la documentation sur les structures des ateliers d'extraction des minerais et de production des métaux reste disparate et n'éclaire que partiellement les étapes de la production. Depuis le III[e] millénaire avant J.-C., la contribution des outils en pierre aux processus métallurgiques est évidente dans les contextes miniers, où des centaines de marteaux ont été utilisés pour l'extraction des minerais, en particulier du cuivre et de l'étain. Associés au phénomène campaniforme, des outils en pierre retrouvés dans les tombes dites « de métallurgistes », accompagnant les défunts, constituent la première preuve de leur participation possible à des activités de métallurgie du cuivre au cours de leur vie. Au début de l'âge du Bronze, les habitats ont livré des outils de métallurgistes, preuve de l'existence d'ateliers dédiés soit à la production de cuivre et d'alliages de cuivre, soit à la fabrication d'objets. Compte tenu des stratégies intensives de recyclage du métal, ces outils en pierre constituent les rares éléments, avec les foyers et les déchets métalliques, capables d'indiquer l'existence d'anciennes zones de production de métal. À ce titre, l'identification de ces ateliers de production élargit le champ des investigations sur les métallurgies, et contribue à éclairer leur organisation au sein des territoires de la fin du Néolithique et du début de l'âge du Bronze, de l'échelle intrasite à l'échelle macro-régionale. L'identification des outils en pierre impliqués dans les processus métallurgiques permet de combler partiellement notre perception de l'organisation de cette activité en Europe continentale. Au-delà de l'évidente adaptation morphologique aux gestes et aux actions, le haut degré de sélection des matières premières est un point commun à tous les outils en pierre impliqués dans des processus métallurgiques. Les roches utilisées pour la fabrication des outils métallurgiques doivent répondre à un large éventail d'exigences physiques, incluant une résistance aux chocs, aux fluctuations thermiques et une certaine abrasivité, variant d'une étape à l'autre de la chaine opératoire.

De récents travaux menés sur les traces d'utilisation et l'analyse des résidus (par ex. XRF, SEM-EDX) de différentes catégories d'outils en pierre (pics, broyeurs, meules, moules, enclumes, polissoirs, marteaux, pierres à aiguiser, etc.) ont permis de préciser les procédés techniques utilisés pour l'extraction des minerais, leur transformation en métal, la mise en forme des objets métalliques et leur entretien. Ils reposent sur quelques référentiels expérimentaux, qui ne couvrent qu'une partie de la diversité lithologique employée pour les outils en pierre et celle tout aussi large de la composition des métaux transformés. Les principaux référentiels tracéologiques portent sur les outils d'extraction minière,

sur les outils de concassage du minerai, sur le façonnage des objets métalliques par déformation plastique et leur finition par polissage.
Comme cela a été constaté expérimentalement, le façonnage des objets métalliques ainsi que le polissage laissent des résidus (cuivre, argent, or) adhérer à la surface de la pierre. Cependant, ils ne sont pas toujours préservés sur les surfaces des outils archéologiques. L'une des raisons de la préservation différentielle des résidus semble liée à la texture et à l'état dans lequel le métal a été travaillé, ce qui renforce ou diminue les liens entre les deux matières en contact. Un autre facteur est lié à la porosité et/ou à la rugosité de la surface de la roche de l'outil, qui offre plus ou moins de possibilités de capturer les résidus dans les parties inférieures du microrelief. Un dernier facteur renvoie à la préservation des micropolis, qui peuvent piéger des résidus métalliques en très faibles quantités. Une stratégie analytique « étape par étape » se révèle ainsi la plus pertinente. Il semble donc préférable de commencer par une détection qualitative de l'absence/présence de ces résidus (par pXRF, par exemple), avant de soumettre les échantillons à des mesures plus quantitatives (XRD ou SEM-EDX). En outre, en fonction de la question archéologique, une cartographie de ces résidus peut être pertinente pour préciser la fonction et la cinétique d'un outil.
A travers différents exemples issus de la littérature archéologique, il apparaît évident que la combinaison d'analyses tracéologiques et de résidus semble la plus à même de préciser la fonction des outils en pierre en contexte de métallurgie. Les analyses fonctionnelles contribuent ainsi notablement à l'identification des outils de métallurgistes et des contextes de production du métal pendant les âges des Métaux. La présence de tels outils dans les habitats, les ateliers, ainsi que dans des contextes funéraires particuliers, nous permet de mieux comprendre l'organisation de la production et le degré de spécialisation des métallurgistes au sein des sociétés du IIIe au Ier millénaire avant notre ère.

Mots clés : métallurgie ; outils lithiques ; âge du Bronze ; tracéologie ; XRF ; SEM-EDX.

European recent Prehistory offers a scenario of deep socio-political changes, in which the rise of institutional power and the development of ruling classes was one of the milestones. In this process of transformation, the rise and spread of metallurgy represented a crucial economic aspect propelling innovative technology and new social and economic relations, mainly from the 3rd millennium BC onwards (Rovira, 2001; Nicolas, 2015; Roberts and Frieman, 2015). Some of the main questions to be addressed in the study of the prehistoric metallurgical *chaîne opératoire* are what kind of ore was exploited (mainly copper, gold, silver, tin), who performed the work, with the aid of which working means and, finally, for what purpose. By answering these questions, research provides critical data about access to natural resources (nature, composition, origin and circulation, control), the organisation of work (communal vs. individual), the technology applied in each stage of the process, and the products derived from it (ingots, ornaments, tools and weapons for elites or more widespread diffusion).

From the 3rd millennium BC onwards, the contribution of stone tools to metallurgical processes is obvious in mining contexts, where hundreds of hammers were used for the extraction of ores, especially copper and tin (Ambert et al., 2011; O' Brien, 2015). Associated with the Bell Beaker phenomenon, stone tools were found also accompanying the deceased in the so called 'metallurgist graves', and constitute the first evidence that points to their possible participation during life in copper metallurgy tasks (Bátora, 2002). With the Early Bronze Age, settlements have provided metallurgists' tools, as evidence of workshops dedicated either to copper and copper alloy production or to object manufacturing (Pernot, 1998; Armbruster, 2010; Drenth et al., 2013; Delgado-Raack et al., 2015; Nicolas et al., 2015; Hamon et al., 2020). Considering the complex and intensive recycling strategies of metal, such stone tools appear to be among the rare elements, together with fireplaces or metal wastes, able to point to the existence of past metal production areas. As such, their identification enlarges the scope of investigations of metallurgies to more unexpected or discrete contexts, and contributes to shedding light on metallurgical organisation within the Copper and Bronze Age territories, from an intrasite to a macroregional scale.

The study of macrolithic material allows insight into metallurgical production, at different stages of the *chaîne opératoire* (Delgado-Raack and Risch, 2008), and into the degree of specialisation of this activity (fig. 1). In prehistoric mining activities, stone is, together with antler, the most important raw material used for dismantling the rock for ore extraction (picks, slings and other percussing tools) as well as for the crushing and first mechanical cleaning of the ore (hammerstones, crushing platforms). From the beginning of copper and gold metallurgy and before the introduction of casting processes, the main metal transformation mechanism was cold plastic shaping through hammering for which the only imperishable tools available were stone hammers and anvils.[1] Some time later, with the introduction of alloys, crucibles and casting moulds became indispensable means of work for which stone was again one of the main raw materials. Stone tools were also needed for the polishing and sharpening of metal objects in the last stages of the metal manufacturing processes.

From another perspective, when metallic objects themselves are not always preserved in the archaeological deposit due to alteration processes and their constant recycling, stone moulds can provide additional data about

1. In these contexts, evidence of metallurgical structures (e.g. kilns) and waste (slag, casting drops) is non-existent and the only elements for an analysis of metallurgical work processes are represented by macrolithic tools or the metal objects themselves, given that the latter have been preserved in the archaeological deposit.

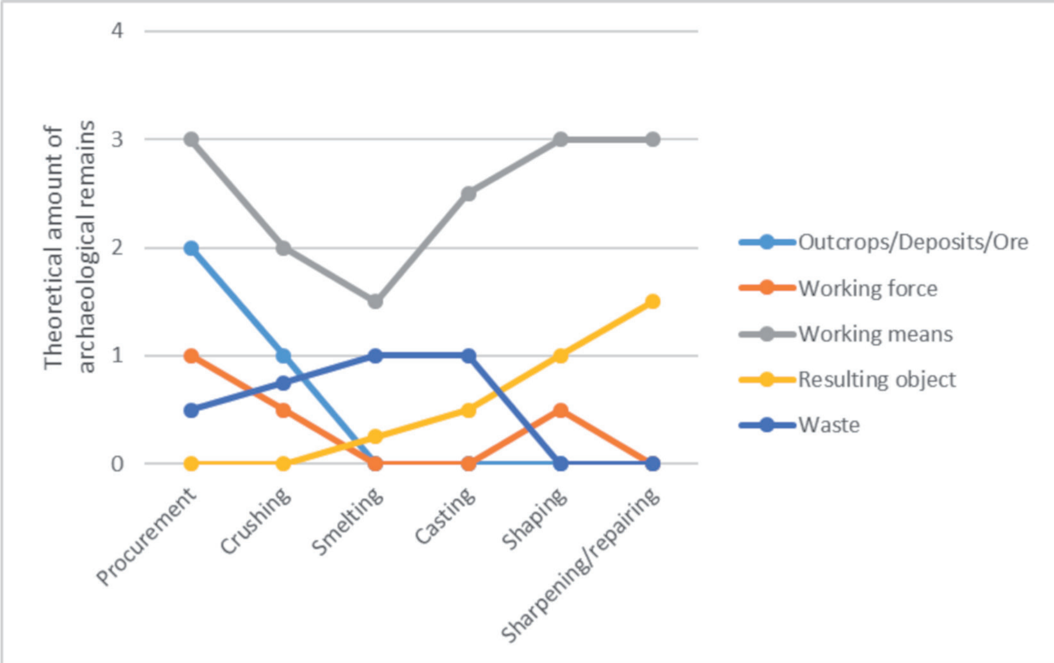

Fig. 1 – Schematic representation of the theoretical quantity of archaeological remains produced in each of the stages along the metallurgical *chaîne opératoire*.

the type of objects cast, as well as their composition (if residues are compositionally analysed). Similarly, although stone crucibles are not as abundant as pottery crucibles (Soriano and Escanilla, 2016), they are generally better preserved than the latter (Contreras et al., 2000).

As a result, macrolithic assemblages offer directly or indirectly valuable information about the development of metallurgical work processes in Prehistory. The heuristic potential of stone tools in the transformation of metal comes from their good preservation in the archaeological record and their ubiquity in the metallurgical work process, from procurement of metallic raw material to the maintenance of metal objects (Delgado-Raack and Risch, 2008).

Throughout this paper, we will offer some insights for the recognition and functional interpretation of macrolithic tools used for metallurgical work processes. Based on several recent case studies, we will discuss the methodological issues for the application of use-wear and metal residues analysis of stone tools from Copper and Bronze Age contexts. The goal is here to contribute as efficiently as possible to the debate on the social and economic background at the base of metal production development.

CONTEXT OF DISCOVERY OF STONE TOOLS, A BIBLIOGRAPHIC REVIEW

Due to the interest devoted in the history of research to funerary contexts, more than half of the evidence available in the literature for metallurgical macrolithic tools comes from graves (74/145, i.e. 51 %; fig. 2). From the 1960s onwards, some authors drew attention to the so called 'metallurgist graves' scattered across Europe, including characteristic grave goods that were directly linked to the manufacturing of metal ornaments, tools and weapons (Butler and Van der Waals, 1966; Semenov, 1969). The study of their content and their mapping allowed the definition of an exclusive phenomenon of primarily adult male graves (with a few exceptions, e.g. Chernych, 2003, Ernée et al., 2020) from the 4th to the 2nd millennia BC, distributed from the Caucasus to the European Atlantic coast and from northern to Mediterranean Europe. The differentiated emphasis put in each region of the continent on some types of grave goods has already been highlighted elsewhere. While in the burials of eastern Europe the first part of the metallurgical *chaîne opératoire*, that is casting (moulds, crucibles, tuyères), is predominantly represented, the second part of the work process, namely plastic shaping (anvils, hammers, sharpeners, polishers), stands out for western Europe (e.g. Delgado-Raack and Risch, 2006). Especially in this region, metallurgist graves reached their critical point during the Bell Beaker and Early Bronze Age i, in a context of an incipient metallurgy. Research recently published with additional graves from central and northern Europe has considerably enlarged the empirical basis for the study of this paneuropean phenomenon (Nessel, 2019). Not only the deposition in graves of specific metallurgical stone tools, metal objects and pottery vessels related to socially outstanding individuals, but also the location of these graves far away from potential ore resources causes them to highlight the social relevance of plastic shaping, finishing and maintaining of metal objects, over smelting and casting operations.

Fig. 2 – Distribution of archaeological contexts with presence of metal plastic shaping stone tools Europe-wide during the 3rd–2nd millennia BC, according to the context of discovery. Data taken from Occhi, 1997, p 520–523; Bátora 2002; Delgado-Raack and Risch, 2006, fig. 6; Freudenberg, 2006, fig. 5; Brandherm, 2009, fig. 1; Freudenberg, 2010, fig. 7; Soriano, 2011, fig. 8; Boutoille, 2019b, with additions after Delgado-Raack et al., 2015; Hamon et al., 2020; Delgado-Raack et al., 2020; Hamon et al., 2021 and Müller et al. ,2023. This map shows a general and not exhaustive review of archaeological contexts in which stone anvils and metallurgical hammers were found. It is based on the publications cited, which provided information about the type of contexts. The two rectangles show the areas studied by Boutoille (2019a) with > 130 sites for France and adjacent countries (A) and Nessel (2019) with > 80 sites for Central and Northern Europe (B). The data from both publications have not been included in the map due to their high density and the absence of systematic information regarding the type of contexts in the first publication.

The publication of these collections helped with the recognition of two concomitant artefact types which participated in the plastic shaping of metal objects through hammering: the stationary piece, represented by the anvils, also known as *cushion stones*, such as were found in Lunteren or Leubingen (Butler and Van der Waals, 1967-1968; Freudenberg, 2006; Boutoille, 2019), and axe-shaped hammers with blunted edge, such as the specimen found in grave 9 at Künzig (Bertemes et al., 2000; Lynch, 2001; Bertemes, 2004; Boutoille, 2012). Moreover, small stone plaques (Muñoz, 2017) and larger slabs (Delgado-Raack and Risch, 2006) have been identified as sharpening tools in graves. Unlike sharpeners, a few specimens have been interpreted as touchstones for the checking of gold quality (Eluère, 1985; Crellin *et al.,* 2022, and for more recent periods in Moravia, see Ježek and Zavřel, 2013).

In contrast to the abundant data coming from funerary contexts, stone tools recovered in settlement contexts including metallurgical workshops (31/145, i.e. 21 %), unknown contexts (36/145, i.e. 25 %) or hoards (4/145, i.e. 3 %) are scarcer.[(2)] Reasons for this could be difficulties in the recognition of such artefacts, which can appear isolated from other discrete metallurgical evidence like kilns, melting waste, etc. Nonetheless, in recent years the systematic application of use-wear and residues analysis has enhanced the visibility of these kinds of tools. In addition, new findings in mines and settlements have enabled new ideas about how the work process for mineral procurement and first cleaning, as well as that for metal plastic shaping, could have functioned (Hamon et al., 2009; 2020; Delgado-Raack et al., 2015; Caricola et al., 2020; Delgado-Raack et al., 2020; Müller et al., 2023; Eguíluz et al., in press).

2. In some regions of Central and Northern Europe isolated findings from unknown contexts seem to be more frequent than funerary contexts (Nessel, 2019). In this case the percentage of unknown contexts in which such tools were found (41/83, i.e. 49 %) surpasses the quantity of graves (39/83, i.e. 47 %), hoards (2/83, i.e. 3 %) and settlements (1/83, i.e. 1 %) with such findings.

MECHANICAL PROPERTIES OF STONE TOOLS AND METALLURGICAL PROCESSES

Beyond their obvious morphological adaptation to gestures and actions, the high degree of raw materials selection is a common point shared by all stone tools involved in metallurgical processes.

Recent research addressing the definition and evaluation of the mechanical properties of rocks participating in percussion and cutting mechanisms show that rock behaviour is determinant in raw material selection (Delgado-Raack and Gómez-Gras, 2017; Delgado-Raack et al., 2019; Monik et al., 2021). Even so, the metallurgical *chaîne opératoire* introduces additional complexity in the technological process. The technology of metal is critically subject to the state in which it is being worked. Depending on the transformation phase, metal working tools will enter into contact with hard rocks (ore mining and mechanical cleaning), minerals in liquid state under high temperatures (casting) and pre-heated or cold metal of different hardness (plastic shaping). Moreover, kinetic environments also change throughout the metallurgical *chaîne opératoire*, from blowing to frictional mechanisms through thermal impact. Following these processes, the raw materials which metallurgical tools are made of must fulfil a wide range of physical requirements for them to achieve the expected results under the best conditions.

Consequently, each category of tool involved in the metallurgical process is subject to rigorous selection. In mining contexts, ore procurement is done with the aid of rather large, massive and tough tools that are highly cohesive and have a hard mineral composition (fig. 3). These tools are usually made of igneous rocks (including volcanic ones), such as granites, gabbros or andesites (Delgado-Raack and Gómez-Gras, 2017, p. 58; Delgado-Raack et al., 2019, table 3; Caricola et al., 2020, p. 7), although especially resistant metamorphic rocks are also sometimes represented in the assemblages (secondarily metamorphosed hornfels). Raw material chosen for casting moulds must be both resistant to high temperatures and easily workable to a casting matrix. In this case, the most used rock types are detritic sedimentary rocks such as sandstones and calcarenites, which are mechanically softer than the previous examples. However, their grainy structure and clay content withstands heating much better than do igneous rocks, avoiding the spread of cracks along the mineral faces. At the same time, they are more easily workable than metamorphic rocks such as slate

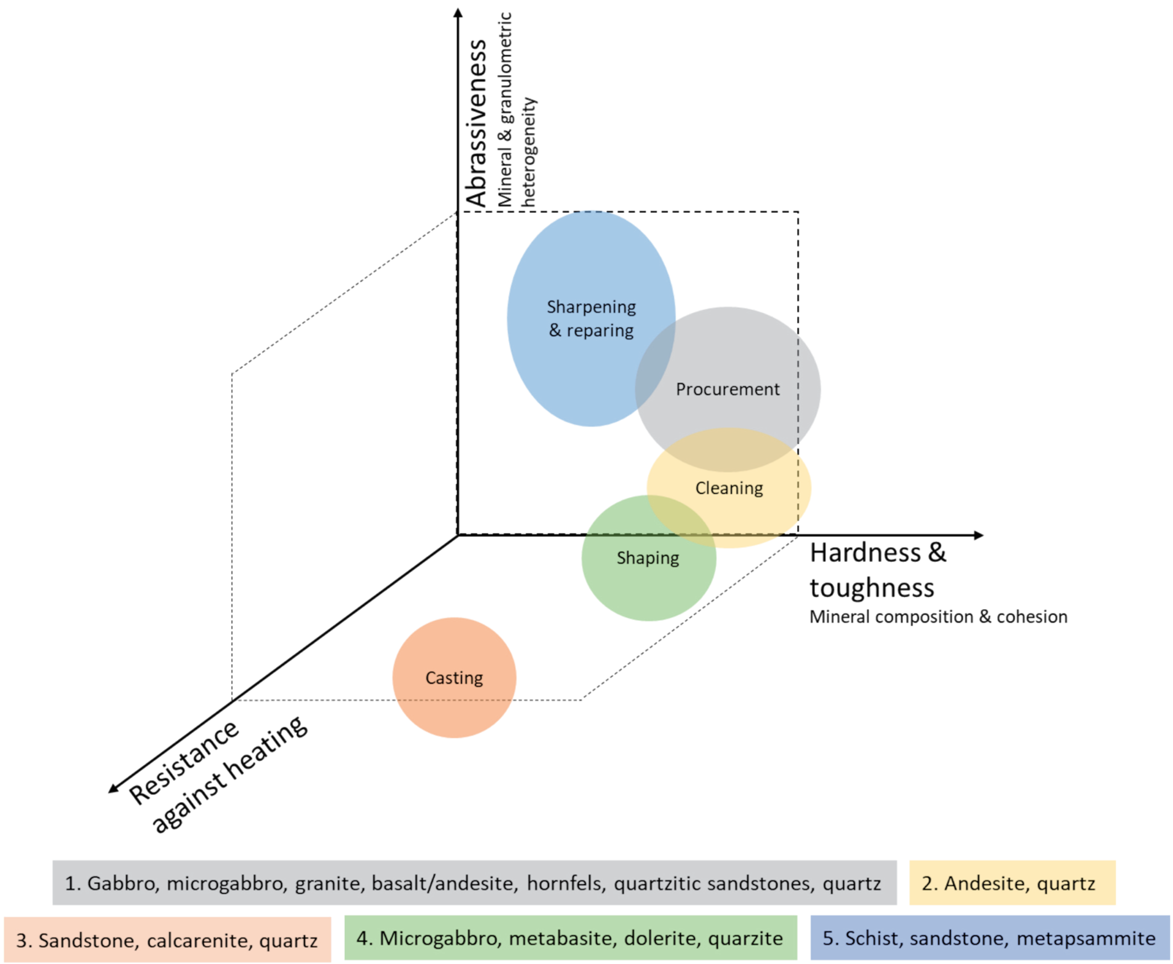

Fig. 3 – Mechanical properties of rocks involved in each stage of the metallurgical process and types of rocks used for them.

or schist. These rocks, although being resistant to high temperatures, include oriented structure or schistosity, which makes the manufacturing process more difficult to control. Tough and cohesive rocks (gabbro, metabasite, quartzite) come into use again for the hammering of metal, though in this case rather fine-grained variants are predominantly used which, opposite to coarser-grained rocks, allow the preparation of smooth working surfaces for the treatment of dainty metal sheets. For the final sharpening and repairing working stages, qualitatively different rocks can be implemented. The roughness of sandstones, metapsammites and schists is used for abrasive purposes, while other more compact materials as mentioned before (fine-grained gabbro, quartzite) can be used for polishing metallic surfaces.

These criteria for raw material choices are of course partly dependant on existing supply strategies and on material availability in a more or less local or regional area around the archaeological sites, implying adaptations towards the better option, and balance between procurement investment and required qualities. One must also note that these raw material choices encompass the use-wear formation process (Adams, 2002; Dubreuil et al., 2015), with consequences for the possibility of conducting functional analysis.

USE-WEAR AND RESIDUES ANALYSIS, A STEP FORWARD

Functional analysis, including use-wear and residues analysis, offers insights complementary to the typological approach to shed light on the contribution of stone tools to metallurgical processes. Based on experimental tests, these approaches are essential to identify a wider range of tools that cannot be isolated within large series solely on the basis of morphological criteria, and thus improve our knowledge of the metallurgist's toolkit. They also help refine the interpretation of tools' function at different steps of the *chaîne opératoire* of metal object production.

Building experimental collections for archaeological use-wear analysis

Reference collections are essential for the interpretation of use-wear traces and the functional interpretation of tools. As a matter of fact, use-wear analysis on metallic objects has faced several obstacles to its development, including plasticity of the metal matter, logistics required for metal production and marked alteration of the surfaces. Consequently, the few pioneer works on metal objects use-wear analysis (Gutiérrez and Soriano, 2008; Gutiérrez and Lerma, 2015; Dolfini and Crellin, 2016) did not pay particular attention to the role of stone tools in metallurgical work processes, including for smelting and casting procedures.

Considering the emerging nature of the recent research on the topic, only a few experimental works, including ours, have been conducted, thus opening the door to a wide field of research to be developed. Functional considerations were first discussed based on ethnographic (Armbruster, 2006) and iconographic data (Boutoille, 2012), in which metallurgical artefacts, their specific morphology, their role in the *chaîne opératoire* and the movements performed with them were defined. On this basis and to go further through experimental works, attention was especially paid to mining and first cleaning of ore (Timberlake *et al.,* 2007; Caricola et al., 2020), metal plastic shaping (Delgado-Raack, 2008; Müller et al., 2023; Hamon *et al.,* 2024) and polishing/sharpening (Delgado-Raack, 2008; Muñoz, 2017; Hamon, et al., 2024). The main lines of each experimental procedure are summarised in table 1.

These experiments faced several challenging issues:

– First, the diversity of stone tool raw materials selected in the different archaeological contexts demands the development of adapted experimental collections, as the nature and properties of the rock have direct consequences on use-wear formation. Macrolithic tools present the challenge of being coarser-grained materials than flint, with a higher mineral heterogeneity in grain size and composition. This implies that mineral particles included in the rock will react differently against wear, developing variable trace patterns in each case. In addition to the grain scale, there are specific aspects of use-wear (e.g., incidence or extension) that can only be observed at the general level. As a result, several observation scales are needed for the analysis of stone surfaces, including low and high magnification approaches according to Adams *et al.,* 2009.

– A second fundamental issue is the variability of metal compositions and their respective mechanical reactions, that also strongly influences use-wear formations. Each group of alloys should be tested separately within experimental protocols, in order to refine the functional interpretation of stone tools that may be used for different metals and alloys, and different steps of their production.

Considering mining activities, experimental protocols did stress different use-wear signatures depending on the nature, composition and texture of the ore extracted. The high level of tool fracture during use engendered longitudinal split fractures, oblique damage or microflake removals that left only part of the active surface preserved (Caricola et al., 2020). For copper carbonate extraction, macropits and macrocracks were the most frequent range of traces, while grains were mostly affected by deep step macrofractures. Micropolishes were accompanied by long and oriented striations, and the traces extended along the top of the grains with smooth texture and flat topography. Copper ore crushing generates fine and random percussion impacts, for which morphology, depth and concentration depends on the texture, size and hardness of the ore (Hamon et al., 2023). Impacts are generally associated with copper residues. A concentrated smooth levelling of the topography is visible. Minerals display fine and dense microfractures. A compact and rough micropolish develops on spots or larger zones.

	Type of activity	Tool type	Raw material	Contact material	Kinetics	Working time (min)	References
COPPER	Copper ore Mining	Percussor, Pic	Igneous and metamorphic rocks	Wall of copper carbonates ores (malachite and azurite)	Perpendicular blows and leverage	90 to 180	Caricola et al. 2020
	Copper ore crushing /grinding	Hammer, anvil	Dolerite, granite	Ore fragments	Perpendicular blows	15 to 60	Hamon et al. 2024
	Copper shaping	Hammer and anvil (shafted in oak trunk)	Gabbro	Copper tube with 1 mm th. wall (pre-heated)	Perpendicular blows	150	Delgado-Raack 2008
	Copper shaping	Hammers	Dolerite, quartz	Dagger, flat axe, palmela point	Deburring (lateral blows), flattenting (perpendicular to oblic blows)	30	Hamon et al. 2024
	Copper polishing	Polisher	Quartzitic and mica schist	Copper sheet	Back and forth friction	120	Delgado-Raack 2008
	Copper polishing	Abraders, polishers	Sandtone, Schist	Dagger, flat axe, palmela point	Back and forth friction	30	Hamon et al. 2024
BRONZE	Bronze shaping	Hammer	Dolerite, quartz	Flat axe, palstave, dagger	Deburring (lateral blows), flattening (perpendicular blows)	30	Hamon et al. 2024
	Bronze polishing	Abraders, Polisher	Sandstone, Schist	Flat axe, palstave, dagger	Back and forth friction	30	Hamon et al. 2024
SILVER	Silver shaping	Hammer and anvil (shafted in wooden block)	Dolerite?	Circular 40 mm diameter sheet of 26.1 g sterling silver (“annealed”)	Perpendicular blows	270	Freudenberg 2009
GOLD	Gold shaping	Hammer and anvil (shafted in pine trunk)	Gabbro	Gold nugget (24 carats) of 3 g (cold)	Perpendicular blows	30	Müller et al. 2023
	Gold polishing	Polisher	Gabbro	Gold sheet	Back and forth friction	10	Müller et al. 2023
	Metal sharpening	Sharpener	Sandstone, Slate, schist	Copper and bronze daggers	_	15	Muñoz 2017

Table 1 – Summary of experiments conducted on different working stages of metal manufacturing in which macrolithic tools are involved, after bibliographic review.

As for metal shaping, experiments highlighted the necessity of rounded and smooth surfaces to avoid any damage to the metal surfaces. For this reason, cobbles are particularly suitable blanks, as they avoid sharp edges that could both break the stone and damage the metal surface. These particular morphologies can be obtained by accurate selection of naturally rounded and weathered pebbles as well as by manufacturing. The manufacturing process of intensively transformed cushion stones has been experimentally reproduced and lasted a total of 80 hours (Freudenberg, 2006). Advantages of such a work inversion in the case of cushion stones could be linked to a longer durability in terms of work intensity or use-life, but this is an issue still to explore.

Experimental stone surfaces used for gold, silver and copper plastic shaping are characterised by highly homogenised and levelled reliefs, due to the pressure created by the perpendicular blows wearing down the most exposed topography to rounded forms (including the edges of previous striations and pits, which are progressively obliterated; Delgado-Raack and Risch, 2008; here fig. 4). Metal particles attached to the stone surface are pushed into anfractuosities. This process provides a shiny reflective surface, often extensively covered by residues, which can partly make it difficult to observe the stone surface directly. These patterns have been recorded on both tools, the anvil and the hammer (Müller, et al., 2023). In all experiments, metal residues stayed attached to the stone surface regardless of the metal object being worked in pre-heated or cold state. Nonetheless, the penetration capacity of residues coming from pre-heated metal is higher, reaching even deeper points of the low topography and enhancing them to cover the relief more intensively. At higher magnification, the surface is covered by a smooth to rough micropitted and microstriated micropolish (Hamon et al., 2023).

Polishing can be clearly distinguished from hammering on both stone and metal surfaces (Müller et al., 2023). The wear mechanism based on horizontal friction favours the development of linear traces on metal and/or stone, shown by fine and dense striations reproducing the direction of motion. Metal particles adhere to high topogra-

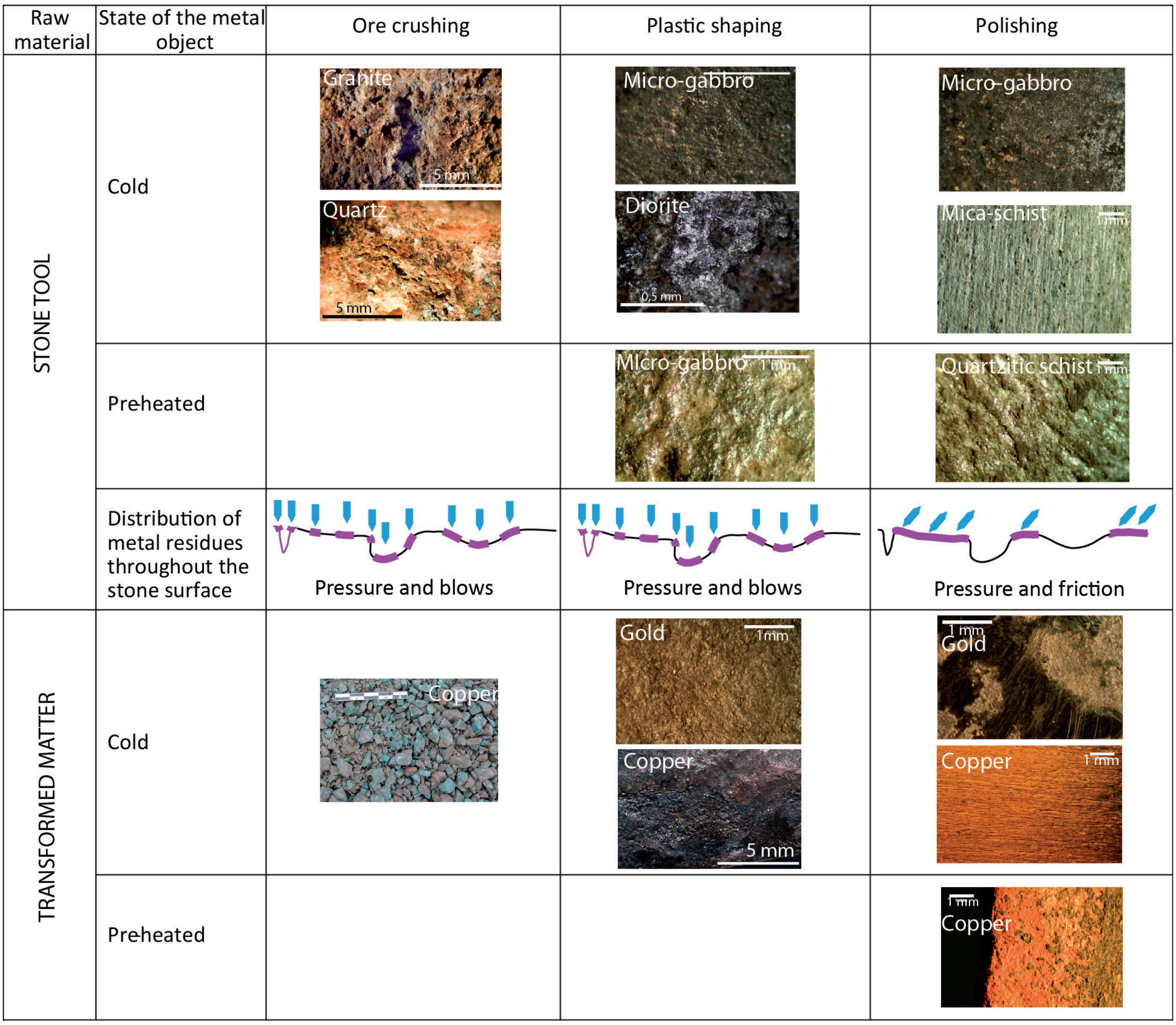

Fig. 4 – Stone and metal surfaces reproduced in experimental metallurgical tasks during copper ore crushing (after Hamon *et al.,* 2024), plastic shaping and polishing (after Delgado-Raack, 2008; Müller et al., 2023).

phy of the stone, although mineralogically heterogeneous rocks (e.g., schistose rocks) tend to slow down this process. On metallic surfaces polished in a cold state, striation patterns appear as a dense weft of fine linear traces providing a smooth and shiny appearance. This effect grows, the finer the grain size and more homogeneous the mineral content of the polisher is. Deeper areas of the metallic surface are left intact as they were hammered. This shows the importance of the previous work step of plastic shaping, as preparatory work to flatten the relief as much as possible. Polishing of metal in pre-heated state does not achieve the same effect at all, although it could help with the flattening of the metal surface in concomitance with plastic shaping.

First results of experiments done on mining/crushing of ore and plastic shaping/polishing of metal need to be expanded in the future in order to test, for example, the same mechanisms with other rock types or other contact materials (mainly varied bronze alloys) or in longer experimentation sequences. In addition, new ways have to be explored that could shed light on specific questions related to the recognition of plastic shaping tools. Especially in the case of highly symmetric tools intensively prepared for use (i.e., the so called *cushion stones*), it remains sometimes unclear whether they were used as anvils or as hammerstones, or even as both. In this sense, we hope a deeper analysis of the qualitative aspects of use-wear and residue analysis will enable researchers to distinguish stationary and mobile tools.

Another major issue is, in certain contexts, the good preservation of residues (Carey et al., 2023). In certain cases, they cover the surfaces below, and all use-wear traces appear inaccessible for analysis. In addition, some residues show intriguing patterns, such as shiny levelled surfaces with micropitting and fine linear striations of variable orientations, that make them occasionally difficult to distinguish from spotted micropolishes (fig. 5a). In this sense, residues can also be informative of the kinetics (percussion, friction, etc.) and nature of contact material of the tools.

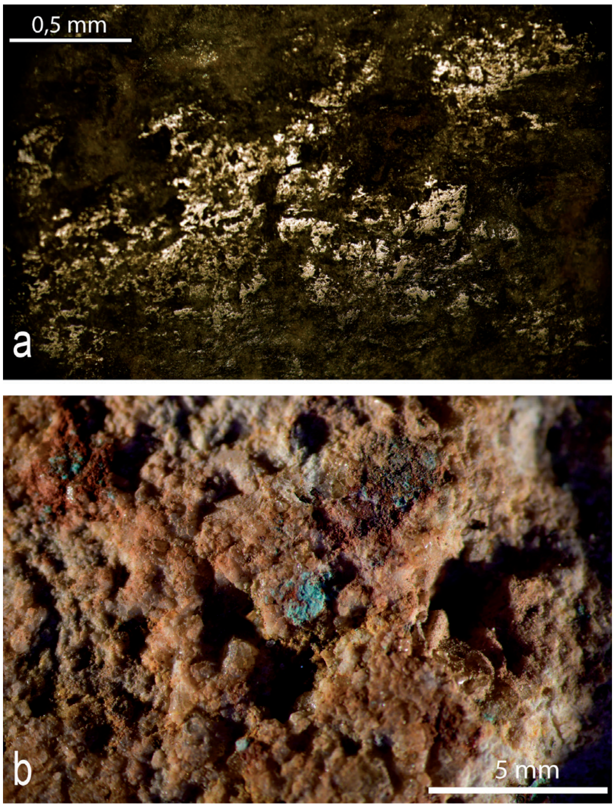

Fig. 5 – Examples for experimental use-wear; a: typical micro-pitted micropolish of copper alloy object shaping on a tool made out of eclogite, including copper residues (after Hamon *et al*., 2020); b: Red and green residues of copper ore on a crushing tool, filling the interstices of the upper and lower part of the microrelief (photo: C. Hamon).

Residues analysis

As was experimentally recorded, metal plastic shaping as well as polishing leaves metal particles (copper, silver, gold) adhered to the stone surface. However, they do not always remain preserved on the archaeological working surfaces. One reason for the differential preservation of residues seems related to the texture and state of the metal being worked, enhancing or diminishing the bonds between the two materials. For example, one is much more likely to find metal residues on casting moulds than on other metallurgical stone artefacts, as melted metal easily enters surface anfractuosities and porosities before cooling down.(3) The manipulation of metal in liquid or viscous state can even lead to contamination of surfaces other than the active one (casting matrix).

Another reason is linked to the porosity and/or surface roughness of the tool's rock, that offers more or less opportunity to catch residues in the lowest parts of the microrelief. This is particularly true for mining and crushing tools, which although being made of highly compact rocks, include rugged active surfaces: first because they are in contact with significant quantities of mineral matter, and second because their use in throwing percussion may create a strong bond between ore and tool's surface.

A third reason is linked to the development and preservation of micropolishes. Some works have demonstrated that a well-developed micropolish can trap metal residues in very low quantities (Hamon et al., 2020). Metal plastic shaping using the tools can be done via cold hammering or via the working of slightly pre-heated metal objects and can therefore provide residues in different quantities and extents restricted to their active surface(s). Definitely, intense or regular retouching processes for the maintenance of the working surface can contribute to the removal of residues, while a low intensity of use can lead to an absence of them.

Additional reasons for the absence of metal residues in archaeological specimens could include the soil conditions in the archaeological deposit. But these mechanisms are not well understood and investigated, and are subject to particular local conditions. On the other hand, metallic elements making up the soil can adhere randomly on the tools' surface. For this reason, it is important to make a thorough record of the location of adherences on broken or natural *versus* anthropic surfaces and on passive *versus* active surfaces. In addition, the recovery of suspected artefacts should always be accompanied by a sampling of the surrounding sediment, in order to evaluate the possible origin of the residues preserved on the stone tool. In this context, it could also make sense to scrape the adhered dust/sediment from the uncleaned surface. Nonetheless, our experience has shown that a bath with neutral soap by fingertip washing and a subsequent rinse with running tap water is not enough to detach or damage the adherences from the stone surface, i.e. does not affect their preservation. Overall, it is convenient to wash the artefact's surface for a proper observation of (a) manufacturing and use-wear traces and (b) possible particles alien to the rock. In fact, the best conditions for use-wear and residues analysis have been provided on clean surfaces, as the detection of the majority of metallic residues has been done until now first optically on previously cleaned surfaces (Delgado-Raack et al., 2015; Crellin et al., 2022; Carey et al., 2023; Müller et al., 2023; here fig. 5b).

One of the main concerns of researchers when approaching residues analysis is the balance between expenses and output. Our proposal, suitable for optimising further analytic investment for compositional characterisation, is to start with the optical tracking of suspected particles adhered to the stone surface. Given that results are positive, throughout the procedure, cheaper, qualitative and non-destructive techniques will be replaced by more accurate ones, including quantitative and maybe destructive measurements (fig. 6). This 'step-by-step' analytical strategy is all the more relevant, as the residues preserved may be very low in quantities. It seems then relevant to start with qualitative detection of absence/ presence of such res-

3. This is also the reason why at compositional level, some more or less volatile metallic elements could appear over-represented in relation to others and *vice versa*.

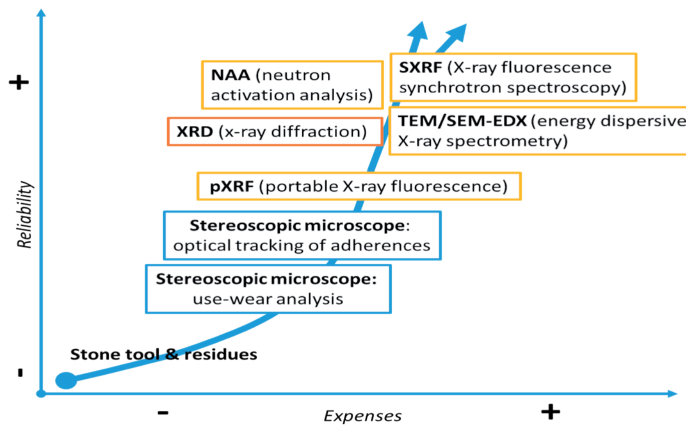

Fig. 6 – Proposed work-flow for residue analysis on stone tools. Blue rectangles stand for optical technique; yellow ones for elemental composition techniques; orange ones for phase composition technique.

idues (such as pXRF analysis), prior to submitting the samples to more quantitative measurements (such as XRD or SEM-EDX analysis). Besides, depending on the archaeological question, a mapping of these residues may be relevant to the precise function of a tool, and its kinetic.

CONTRIBUTION OF STONE TOOLS TO THE *CHAÎNE OPÉRATOIRE* OF METALLURGICAL PROCESS

On the basis of extensive literature on the topic, it is now possible to draw a quite precise panorama of the role of stone tools in the *chaîne opératoire* of metallurgical processes, from ore procurement to tool sharpening.

General pattern

Striking is the existence of relatively specialised categories of tools at each stage of the production, that appear non-interchangeable (table 2). As a matter of fact, the hammers used to process ore and reduce it into small fractions do definitely not offer the same characteristics as the hammers used to flatten, thin and regularise the metal objects' surface. Moreover, different sets of tools can be chosen for better efficiency in the processing of ore, or in the finishing action on metal tools, mainly by considering the results expected. The know-how associated with the forging or with the finishing stage implies a relatively high diversity of tool types, that ensure accuracy of the gesture, as well as reliable results. This diversity of tools with characteristic morphologies also expresses different ways

Task within metallurgical *chaîne opératoire*	**Mechanism involved**	**Macrolithic artefacts involved**
Procurement (mining, collecting)	Mechanical dismantling of rock	**Maces** **Picks** **Slings**
Processing, Cleaning (crushing)	Mechanical break up of ore carrying rock	**Maces** **Pestles** **Crushing tools** **Mortars** **Stone slabs** **Grinders**
(Roasting / Smelting)	(Heating ore)	**(Ovens; burned plaster)** **(Reduction vessels)**
Casting or melting	Heating ore	**Crucibles** **Molds**
Plastic shaping	Mechanical shaping of cold/hot metal blank through pressure/blows	**Anvils** **Hammers**
(Tempering / annealing)	(Heating & cooling up metal object)	_
Finishing	Sharpening Polishing Decorating	**Sharpeners (whetstones & slabs)** **Abraders** **Polishers** **Touch stones**
Maintenance	Re-sharpening Repairing	**Sharpeners (whetstones & slabs)** **Abraders** **Polishers** **Touch stones**

Table 2 –Schematic role of the main category of stone tools employed at each stage of the metallurgical process.

of doing things amongst the workshops and groups of producers, following a chronological or regional pattern.

Procurement: mining, collecting and crushing ore

Most of the stone tools involved in ore extraction during the Copper and Bronze Age reflect not only direct adaptation to the rock available locally to obtain tools resistant to throwing percussion, but also adapted morphologies of the active surfaces as well as systems of handling, to extract ore. Most of these adaptations and characteristics of stone tools depend on the type of outcrop and on the organisation of the extraction system (open-air, subterranean, shaft etc.) and of the mining communities (size of the groups, rate of control, frequency and seasonality, volume extracted, transportation, etc.). The example of the copper carbonate extraction in Grotta della Monaca, Southern Italy (Caricola et al., 2020) illustrates perfectly how the weight and morphology of the tools' active surface was deliberately adapted to the specific configuration of each mineral outcrop, as confirmed by use-wear analysis. Use-wear analysis demonstrated that tools were used for the exploitation of different outcrops and types of minerals: heavy tools for the excavation of calcite planes and middle-size tools employed in the excavation of mixed deposits, while the active surface in contact with copper ores was significantly reduced.

Copper crushing and cleaning operations

Throughout Copper and Bronze Age contexts, the processing of ore and its reduction into smaller fractions prior to smelting generally requires stone tools.(4) They require blocks of dense and non-contaminant rocks, resistant enough to ensure efficient crushing of sometimes very hard mineral matter. They also generally show an association of percussion impacts and of strongly smoothed surface due to an association of crushing (throwing percussion), pounding (throwing and resting percussion) or grinding actions (resting percussion), that can alternate through the process while the size of ore fragments is getting more and more reduced. Most tools involved in ore crushing and grinding share common points with the processing of semi-hard mineral matter, such as step fractures and grain levelling (Carey et al., 2023). Analysis of such numerous crushing tools on the Chalcolithic exploitation of Cabrières, Hérault, France (Hamon et al., 2009) pointed to them probably being pre-shaped by pecking, prior to being used for crushing and then grinding. They attest to the presence of a workshop, close to the extraction mines, in order to produce copper metal. Their functional analysis points to possible use for ore reduction but also the sorting and cleaning of small particles of smelted copper considering the presence of heating traces on the active surfaces (fig. 7). Though use-wear analysis pointed optically to the random presence of copper residues in the anfractuosities of some tools' active surfaces, the XRF analysis did not manage to detect the presence of 'greenish' and altered copper elements. As suggested, this may be due to the too low quantities of copper residues preserved, and their high rate of dissolution in the superficial water. This lack of copper residue detection on crushing tools can be more problematic, especially in regular settlement contexts where crushing tools and anvils could have been used for other purposes. There, their identification as metallurgists' tools is crucial, as they allow identification of discrete metal production that is barely visible through other remains, as in the case of the Early Bronze Age sites in Brittany (Hamon and Blanchet, 2015; Hamon et al., 2020; 2021).

Casting

Moulds have been frequently deposited in the so called metallurgists' graves throughout Europe (Bátora, 2002), and are frequently found in hoards (Boutoille, 20090; 2012) or settlement contexts throughout Europe. But very few works have combined use-wear and residues analysis to get more into the details of their use, considering the small group of challenging issues related to the function of this type of objects. Consequently, archaeometric analyses have generally been conducted to determine the composition of clay moulds. However, some works have been carried out on the metallic surface residues, to explore their composition and thus the origin of the ores entering production. As an example, we will cite here two recent works illustrating the potential of different archaeometric methods to analyse residues on moulds. The chemical composition of preserved layers of metal on two moulds from Late Bronze Age graves in Poland was investigated using ED-XRF and SEM-EDS analysis. This work highlighted that several metal objects with different compositions were cast in the same moulds (Nowak et al., 2022). Another archaeometric analysis combining XRF, SEM-EDS, Micro-FTIR and Micro-Raman has explored the nature of some black residues on a Late Bronze Age mould surface from Galicia, NW Spain (Figueiredo et al., 2021). It allowed determination of the nature of the alloy and the type of object cast as well as showing some preparation of the surface of the mould with carbonised bone deposits in order to smooth the surface during casting.

Plastic shaping

Hammers and anvils are concomitant tools needed for the plastic shaping of metal objects (Armbruster et al., 2003).(5) The anvil is the stationary element, which had to be often fixed in a wooden stump, especially the smaller specimens (Armbruster et al., 2019). The blows

4. The typical crushing tools, with their central 'cupule' for throwing percussion impacts, can be either the upper or lower part of the crushing system, though this is generally difficult to determine on archaeological tools.

5. It cannot be ruled out either that tools of other raw materials, such as wood, could have acted in concomitance with them.

Fig. 7 – Examples of crushing tools and use-wear; a: basalt crushing tools from Cabrières (Hérault, France), detail of macroscopic use-wear face and cupule side (after Hamon *et al.,* 2009); b: diorite crushing tools from Plonéour-Lanvern (Finistère, France; after Hamon *et al*., 2021).

performed with the hammer as the mobile part of the equipment were aimed at morphologically modifying the metal, through drawing, bending, edging, cutting, punching, flattening, etc. Pressure processes acting in this mechanism lead to changes in the interior structure of metal, which is recognisable through metallography in the specific oriented appearance of the dendrites inside metal objects (Rovira Llorens and Gómez Ramos, 2003; Montero and Rovira, 2013). Such data suggest that during the Copper Age and the first part of the Bronze Age manufacturing of metal objects was mainly based on cold hammering, combined sometimes with annealing.

The density of the rock selected as well as the morphology of the active surface of the tool are directly adapted to the different hammering actions, considering the diversity of actions and gestures associated with this stage for different kinds of objects (Armbruster, 2000, p. 49). In general terms, straight surfaces will accomplish the flattening of the contact surface, displacing the metal laterally, while a convex morphology will favour the curving or bending of the surface (Boutoille, 2015). Active surfaces of anvils tend to be located on the widest sides of the tools (obverse or reverse) and are straight or slightly convex. Hammering fronts include a higher morphological variability between straight and very pronounced convexity; they are usually narrower and can appear installed on different sides of the contour. Nonetheless, it is not always possible to discern between passive and active tools based on morphometrical parameters, as anvils and hammers constitute two closely related artefacts, some of which could have functioned in both ways.

All metal shaping tools fulfil at least two requisites: (1) their physical properties make them mechanically resistant against blows and (2) their highly smooth surfaces ensure the integrity of the metallic objects to be shaped without damaging them. Following these technological parameters, different types of tools can be distinguished. One of the most widely known types is represented by so called *cushion stones* (Butler and Van der Waals, 1967; Freudenberg, 2010), the name being highly expressive of their most important characteristic, namely their regular 'padded' appearance. All their surfaces were intensively prepared before use and more than one (or even all of them) could have been used for metal plastic shaping. Acute as well as right angles were erased through friction and converted to facets (fig. 8). Although they appear in earlier contexts such as the Bell Beaker (Fitzpatrick, 2011) they are typically associated with Early Bronze Age richly equipped graves such as Leubingen or Lunteren, central Europe (Butler and Van der Waals, 1967) or Los Cipreses, southwestern Europe (Delgado-Raack and Risch, 2006). The second type of tool has been frequently addressed as 'axe-shaped hammer with blunted edge' (Bertemes et al., 2000; Lynch, 2001). These hammers are equipped with a smooth active front instead of a cutting edge and were unequivocally used as the mobile part of the metal plastic shaping equipment. Such specimens have been frequently recorded from the Copper Age onward in Bell Beaker grave contexts (e.g. Künzig-Bruck, Bavaria; Bertemes, 2004) as well as in settlements (e.g. Cerro de la Virgen, Iberian Peninsula; Delgado-Raack, 2013), and also at other European Bronze Age sites (Boutoille, 2015; Hamon et al., 2020; Eguíluz et al., in press). Further types of tools are clearly

Fig. 8 – Metal plastic shaping stone tools from Bruszczewo (Poland; Delgado-Raack et al., 2020); Tira del Lienzo (Murcia, Spain), lateral view of the tool (Delgado-Raack et al., 2015); Los Cipreses (Murcia, Spain) (photo: Jesús Gómez Carrasco, 2005, Photographic Archive of the Archaeological Museum of Lorca); and Gatas (Almería, Spain; Delgado-Raack, 2008). Arrows indicate manufacturing facets; dotted lines indicate hammering surfaces.

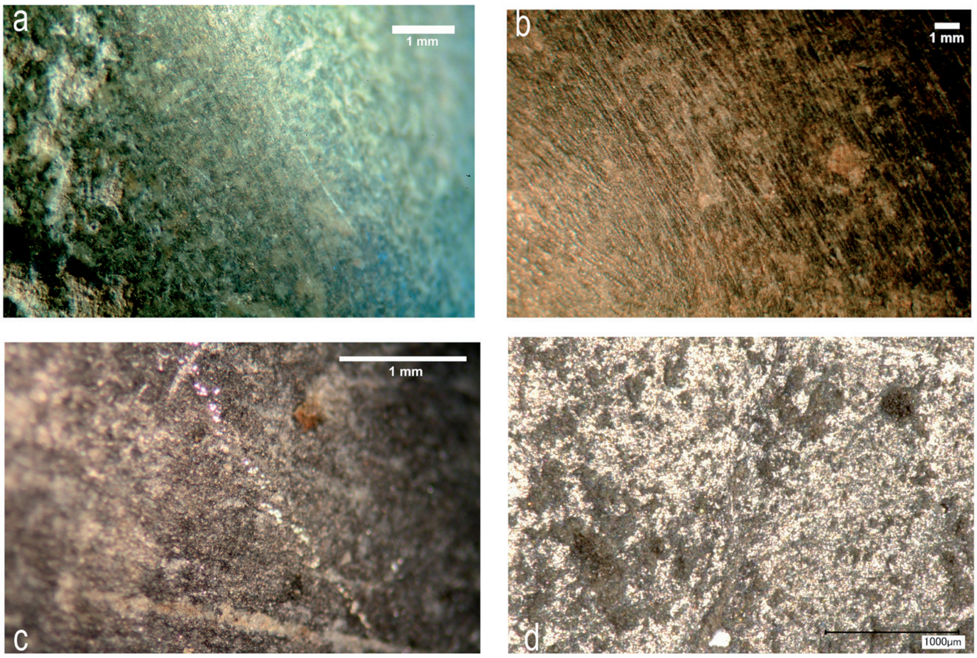

Fig. 9 – a: Hammer with blunted edge showing on its active front fine oblique striations (manufacturing traces) cut by pitting (use-wear traces; Delgado-Raack, 2008, fig. 4.1.66); b: Cushion stone covered by fine and dense striations (Delgado-Raack and Risch 2006, fig. 2); c: Silver linear trace located on a hammering surface (Delgado-Raack et al., 2015, fig. 5e); d: Gold remains filling up anfractuosities on anvil (Müller et al. 2023, fig. 7d).

more irregular in shape. This is the case of former stone battle axe heads which were reworked into metallurgists' tools in the Wessex culture in Great Britain (Crellin et al., 2022) and other broken pieces of artefacts, which were reused as anvils in the Únětice culture of Central Europe (Eguíluz et al., in press). Finally, thanks to use-wear and residue analysis, a series of plastic shaping tools have started to appear in the archaeological record that, contrary to the previously mentioned artefacts, were made of naturally rounded cobbles. Examples of this kind of tools have been documented, for example, in Bell Beaker graves from Hulín – Pravčice 2 (Peška, 2016, fig. 13), in the Bronze Age grave of Upton Lovell G2a (Crellin et al., 2022) and at the Iberian site of Gatas (Delgado-Raack 2008, fig. 4.1.66). Moreover, experiments have shown that the use of unmodified cobbles in metal plastic shaping is viable as they ensure a high degree of homogeneity of the rock (Müller et al., 2023).

Although metrical and use-wear analysis[(6)] have not been developed systematically, the available data include a wide metrical variability among the cushion stones ranging between 50 and 200 mm (Risch, 1995; Delgado-Raack et al., 2015; Ache, 2019). According to this, the active surfaces of some *cushion stones* are much larger than hammers while others fall in the same metrical group as the latter, offering only narrow or reduced surfaces for work. This means that they were probably embedded in a wooden stump as a stationary element, and were often extracted, rotated and inserted again or even used as a mobile tool. It is likely that metrical variability of the tools was linked to (a) the type of metal (gold, silver, copper, bronze) and (b) the type and/or size of the object to be transformed (ornament, weapon/tool). In this sense, lighter artefacts would be suitable for soft, precious metals such as gold (Boutoille, 2019), while larger surfaces corresponding to heavier tools would be needed for metal tools or weapons.

Besides the mentioned technological variability, all specimens analysed under the scope of use-wear seem to have common trace patterns regardless of whether they have wide or narrow fronts (facets). According to the recording system published by Adams et al., 2009, active surfaces display sinuous to flat topographies and regular microreliefs, in which abrupt slopes are absent. The most frequent use-wear pattern includes linear traces, strong levelling of minerals, polish, adherences and pitting. Following the chronological order of appearance, dense and shallow linear traces are still recognisable as remains of preparation of the surface before use (fig. 9b). Their distribution can be concentrated or covering and their borders have been gradually worn and smoothened due to the regular pressure of hammering with a softer material (metal) in between (Delgado-Raack and Risch, 2008, fig. 4). In the case of narrow active fronts of the axe-shaped hammers with blunted edge, these striations are oriented parallel to the longitudinal axis of the facet. The process of plastic deformation of metal objects itself provides the active surface with a homogeneously levelled aspect and a covering and highly reflexive polish with a close or even connected density (Delgado-Raack et al.,

6. Many publications refer to the general metrics of the tools, but few include the dimensions of the actual active surface involved in work. In a similar way, systematic descriptions of use-wear are still scarce for metal plastic shaping tools. This makes comparison of large data sets still difficult.

Site/Grave	Chronology	Artefact type	Residues	Bibliography
Groß Sarau (Northern Germany) – Dredging finds	Late Neolithikum (LNI)	2 anvils	Cu, Fe	Freudenberg 2009
Künzing-Bruck (Bavaria, Germany) – Grave 9	Bell Beaker	1 hammers	Au (75%), Cu	Bertemes et al. 2000; Bertemes 2004; 2010
Těšetice, Turovice (Moravia, Czech Republic) – Graves	Bell Beaker	2 anvils	Cu, Au alloy	Batora 2002: 199, 205 (cited in Peška 2016)
Hulín 1, Hulín-Pravčice 2, Opatovice (Moravia, Czech Republic) – Graves	Bell Beaker	2 anvils Several anvils	Cu, Au, Ag	Peška 2016
Hengelo – Elderinkweg (Netherlands) – Hoard	Bell Beaker	2 anvils and 1 whetstone	Cu, Au	Drenth et al. 2013; 2016
Zwenkau (Central Germany) – Cremation burial 1	Bell Beaker	1 hammers (nr. 32)	Au (42%) Ag (41%) Cu (16%)	Hänisch & Schneider 2005 (cited in Conrad 2009/10)
Hulín 1, Hulín- Pravčice 2 and Opatovic (Moravia, Czech Republic) – Graves	Bell Beaker	Several anvils and hammers	Au, Ag, Cu	Peška 2016
Milukovice 12/10, 13/8, 36/204, 60/6 (Bohemia, Czecj Republic) – Graves	Bell Beaker	4 pebbles / hammers	Au, Ag, Cu, Sn, Pb, Zn	Ernée et al. 2020: Tab. 40b
Franzhausen (Austria) – Graves	EBA	Several tools	Cu	Martin 2014
Upton Lovell G2a (England) – Grave	EBA	1 anvil and 1 hammer	Au, Cu	Shell 2000; Crellin et al. 2022
Tira del Lienzo (Iberian Peninsula) –Workshop	EBA	1 anvil/hammer	Ag (mainly), Cu	Delgado-Raack et al. 2015
Ploneour-Lanvern (Brittany) – Settlement	EBA	1 hammering and polishing tool (nr. 15)	Cu, Zn	Hamon et al. 2020
Tremuson la Colignière (Brittany) – Settlement	EBA	2 hammering tools	Cu	Hamon et al. 2021
Lannion Bel Air (Brittany) – Settlement	EBA	2 anvil, 2 abraders 2 hammering tools	Cu	Hamon et al. 2021
Bruszczewo (Poland) – Settlement	EBA	1 anvil	Au, Ag, Cu	Müller et al. 2023
Humanejos (Iberian Peninsula) - Grave	Bell Beaker	1 sharpener / whetstone	Cu	Muñoz 2017

Table 3 –Summary of cases in which metal plastic shaping stone tools have provided metallic residues.

2015). This glossy polish affects the most exposed points of the relief without reaching the deepest anfractuosities. Small impacts of percussion and isolated striations can appear scattered along the surface. Their interior is not as dark as the former preparation traces, and they clearly cut into the polished relief, evidencing occasional and accidental direct contact between both stone tools during work (fig. 9a).

Residue analysis can provide complementary data to use-wear analysis on gesture, angle, orientation and contact surface between the stone tool and the metallic object and is additionally relevant for the definition of the kind of metal worked. According to the published works (table 3), the quantity and nature of the preserved residues are diverse, and their comparison difficult to establish considering the numerous taphonomic biases involved in their preservation. Nonetheless, their preservation on the stone surface stands for a direct contact between stone and metal (hammering), opposite to the indirect contact (sheeting), which uses a layer of a flexible and thin material such as for example leather interposed between stone and metal (Perea, 1995). Given that they have been optically recognised and described at mesoscopic level, at the present state of the research two kinds of adherences can be noted. On the one hand, and most frequently, metallic residues appear as a bright and glossy linear trace of continuous or intermittent distribution overlapping former use-wear traces (fig. 9c). Their formation should be understood as an effect of accidentally scratching the metal object against the stone, similarly to the isolated striations mentioned above. On the other hand, residues stay adhered to the stone as tiny particles of plastic appearance loosely scattered or concentrated in certain areas. Examples of residues recorded up to now exhibit a matte green colour when they have a carbonatic composition (malachite) or are shiny (gold and silver).

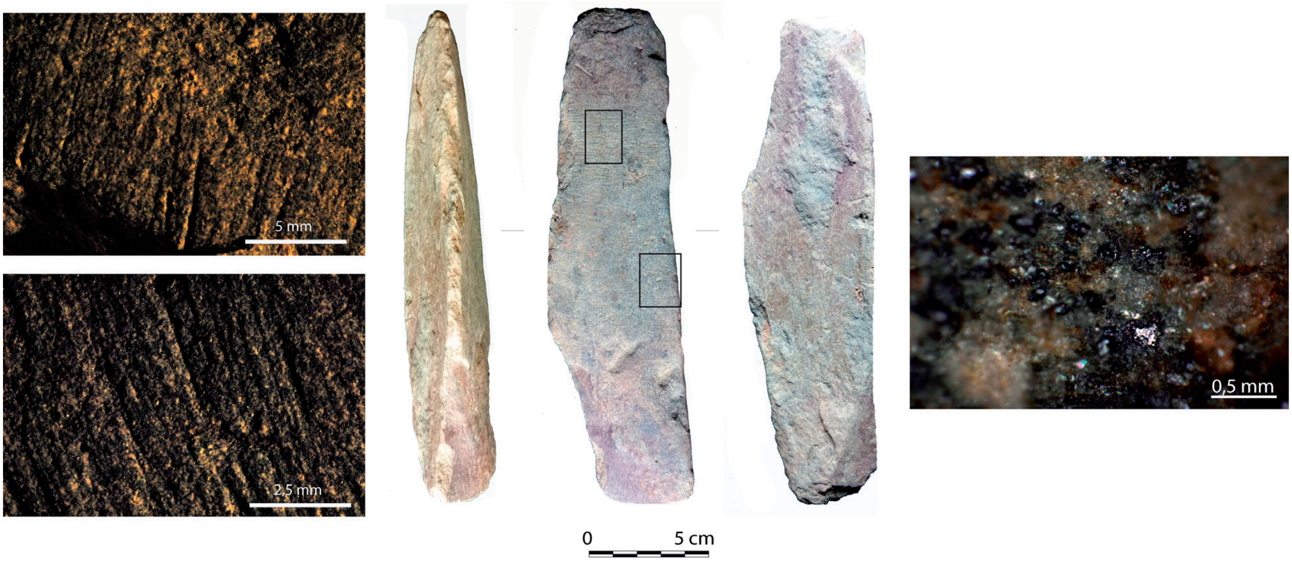

Fig. 10 – Example of finishing tool: sharpener on schist sandstone from Lannion (Côtes-d'Armor, France; after Hamon et al., 2021).

When they are sufficiently developed, residues can additionally suggest the gesture, as most of them remain in the anfractuosities of the topography after being pushed through hammering pressure (fig. 9d). Both distribution patterns of residues can be clearly distinguished from other patterns involving regular friction on metal (Müller et al., 2023). It is important to highlight that distribution and density of residues is not necessarily coincident with the distribution and density of the glossy polish mentioned above.

From the technical point of view, the position of metal plastic shaping in the metallurgical *chaîne opératoire* must have accumulated a high production value, judged from the final stages of metal manufacturing. At this stage metalworkers managed already transformed raw materials in society (mined, cleaned, smelted) and applied their technical knowledge and expertise, which was limited to a reduced part of the population. This included, among other things, controlling the mechanical properties of gold, copper and silver and, later on, bronze, under hammering mechanisms and especially when annealing was involved. In fact, the non-linearity of the plastic shaping constitutes the main difficulty of the task when it comes to conferring the desirable proportions, resistance and hardness on the metal object (Mohen, 1992, fig. 53; Coghlan, 1975, p. 90).

As research in the European continent on plastic deformation of metal goes on, this picture starts to diversify. Some data available for Copper Age Iberian settlements could suggest the existence of workshops managed at collective community level (Delgado-Raack, 2013). The most frequent types in this period are the axe heads with blunted edge. Although Bell Beaker graves equipped with anvils and/or hammers tend to include prominent grave goods, for specific regions such as Moravia it has been stated that the figure of the craftsman could have been subjected to a 'popularisation' process (Peška, 2016, p. 15). Some examples of stone tools with metal residues suggest that they were actually used before being included among the grave goods. The production devoted to metallurgical stone tools reached its climax during the Early Bronze Age, when they were most accurately manufactured, as several prominent graves show (Leubingen, Lunteren and Los Cipreses). Whether the buried individuals took an active part in metal plastic transformation or symbolically took over this role should be addressed in the future through (a) the enrichment of the empirical basis on systematic use-wear and residues studies of stone tools, and (b) other approaches such as anthropological ones (e.g. enthesopathies). For Early Bronze Age settlements, a dichotomy arises based on the coexistence of both workshops specialised in certain manufactures addressed to the elite (e.g., metallurgical and textile production; Delgado-Raack et al., 2015) and small workshops in which plastic deformation of metal took place at small scale (Hamon et al., 2020; 2021).

Finishing

For finishing operations, abraders, polishers, smoothers and sharpeners can be diversely used to shape, regularise or homogenise the surface of metal objects. Depending on the expected surface effect, the rocks selected can be abrasive and granular, to take off matter, or on the contrary very dense and regular, to smoothen the metal object's surface. The tools used are generally of elongated shapes, used in a transversal or longitudinal motion as suggested by the numerous striations covering the surface of these stone tools (fig. 10). In some cases, longitudinal grooves in the centre of tools or transversal incisions on their lateral edges can be visible and suggest the complementary use of different parts of the objects to shape their sides and edges.

The category of sharpener, used rather during the metal tools' life than during their shaping stage, is a little apart: their presence within assemblages and settlements should be more frequent, considering the regularity of their everyday use. In contrast to other types of tool, metal polishers and sharpeners offer less probability of finding residues on their active fronts. In a functional study on perforated stone plaques from Bell Beaker funerary contexts found at the Iberian site of Humanejos, the author reports the observation of copper residues on sharpeners made of sandstone, slate and schist before cleaning and after 15 minutes experimentation, while only one out of 10 archaeological specimens analysed bear metal residues (Muñoz, 2017, p. 22 and 28-29).[7] One out of three whetstones analysed from a hoard context in the Bell Beaker site of Hengelo provided metallic residues (Drenth et al., 2013).

DISCUSSION AND PERSPECTIVES

The development of such investigations on the role of stone tools in metal object production should follow some guidelines in the future.

We cannot stress strongly enough the necessity of combining use-wear and residues analysis to obtain a complete overview of the tool's functioning. Another key point relies on the use-wear analysis of large series of tools, as the only reliable analytical strategy to detect possible candidates for metallurgists' tools. This use-wear approach combined with experiments can help detect ways of doing things specific to certain groups of craftsmen and workshops. Combined experiments and use-wear analysis of stone and metal objects would together be essential to refine the observations and test their plausibility and their relevance in regard to the characteristics of the finished products (Dolfini, 2011; Gutiérrez-Saez and Lerma, 2015). Then, on the basis of the identification of macroscopic residues or of best preserved micropolished surfaces, compositional analysis can be conducted by SEM-EDX, XRF or XRD, to refine the type of metal processed, and possibly determine the elements entering into its composition. The results could contribute to the discussions on possible small-scale exploitation of ores, in regions where they are suspected though their presence is not fully demonstrated (Le Carlier de Veslud et al., 2017).

To avoid interpretative bias, and enlarge our panorama of the contexts of production of the first metallurgies, such analysis should not only focus on mines or graves, but also consider stone tools found in settlement contexts. This should help track contexts of small-scale metallurgical production, linked or not to domestic units, and that are generally neglected or simply not clearly highlighted within the archaeological record, especially for the first copper production (Gandois et al., 2019; Obon, 2020). This observation is particularly true in the eventually frequent case of spatial segmentation of the metallic production. The smelting and casting operations have a particular connotation, due to the fireworks required, and their transformative value from rock to metal, and from metal to object. In contrast, sharpening and repairing should not be considered relevant clues, considering their daily use. Nonetheless, among shaping tools, a series of findings in certain European regions point towards a domestic development of some of the metallurgical tasks, which opens the door to a scenario of more widespread activities among Bronze Age communities than initially suspected.

To open new perspectives, a series of still pending questions can be listed.

First, the question of the arrival of metal on sites is key to understanding better the exchange routes and their structuration: detecting if ore or metal was circulating, and in which format it arrived at the sites, is of crucial importance in discussing the control of the resource and its exchange routes. By the time metallurgy was starting to expand in Europe, there are some examples that suggest ore was travelling long distances from the raw material source to the final context of use (e.g. silver in Tira del Lienzo: Delgado-Raack et al., 2015; gold in Bruszczewo: Müller et al., 2023). Whether metal circulated as ore, ingots or even half-finished products is also a matter of a wide analytical scope that should be carried out at superregional level.

Then, the shaping of objects in cold or pre-heated state is still not completely solved, and the choice of such or such technique is still under debate. The organisation of workshops and the transmission of the craftsmen's know-how is also still to be explored, to better understand the networks of mastering of these technologies, especially for the late Neolithic/early Chalcolithic periods. With the Bronze Age, the metal progressively replaced stone as a major mineral matter to exchange. The stone tools involved in metallurgical production are in the end a minor part of the general stone assemblages, but these particular implements are specifically selected to be buried in graves, to materialise the particular function or status of the deceased. The function of perforated stone plaques as possible sharpeners should also be subjected to systematic use-wear analysis, as they constitute emblematic objects, in Bell Beaker and Bronze Age graves (Butler and Van Der Waals, 1966-1967; Bátora, 2002; Turek, 2004; Fitzpatrick, 2011; etc.). As such, the tools may be considered as signature-objects, and the deceased as possible specialists.

From the point of view of the social role played by craftsmen, the mere fact that metallurgy was performed in regions where metallic ore was non-existent, must have implied that the artisans of this exotic raw material were special individuals in society. The so called 'metallurgist graves' are almost all related to adult males, who could have gained a long apprenticeship and enough expertise during their lives in order to directly perform such work processes. Taking for granted the direct participation of such individuals in the metallurgical work process and the remote distances existing between natural metal sources and some of the 'metallurgist graves', the possibility cannot be ruled out that these men moved within the wide system of exchange networks offering their know-how

7. This sharpener was recovered from a burial in direct contact with a metal dagger, although metal remains were preserved not only on the contact surface but also on the back of the tool. This should stand for a functional origin of the residues.

and services to the population of different countries (e.g. Amesbury: Fitzpatrick, 2011).

Finally, the reconstruction of the detailed *chaîne opératoire* of production along with a systematic study of skeletal remains (enthesopathies) should help clarify the relationship between metallurgical work and the most prominent figures buried in rich graves with abundant metal objects and the labour means needed for their manufacture. If they were not the direct executors of the metallurgical work, they were at least able to remove from the productive process not only a whole series of specialised work instruments but also weapons, tools and metallic ornaments, and keep them out of circulation, in a certain form of control.

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