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Making Bronze Age Solid-Hilted Swords: From *Chaînes Opératoires* to Craftspeople

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Abstract: Investigating the organisation of production of Bronze Age metalworkers is challenging because of the lack of direct archaeological traces related to bronze production. Workshops are scarcely excavated and are mostly known indirectly through waste pits containing leftovers from the production such as moulds fragments. Studying the context of production must therefore rely on indirect evidence coming from the artefacts themselves. One type of object can indeed be produced using different techniques. These technological choices are not only influenced by crafter's creativity: they also depend on socio-cultural factors. This makes possible the identification of production groups through common technological choices made at different steps of the chaîne opératoire, i.e. groups of metalworkers sharing common techniques and know-how. A recent PhD thesis by the author provides an overview of the production techniques of Bronze Age solid-hilted swords in Europe (Dumont, 2022). This paper aims at summarising the main results of this study. Using X-ray imaging techniques, such as radiography and CT-scan, as well as data from published studies, technological data of 634 swords in Europe out of 2,588 currently listed was collected. A technological classification framework was created to identify different chaînes opératoires. Using this new tool, it is possible to study of the evolution of the organisation of production of these swords throughout Bronze Age Europe. Three main phases are identified. The experimentation phase (1800–1450 BC) is characterised by several small-scale production units and a low technological standardisation. The monopoly phase (1450–900 BC) shows a stronger technological and stylistic standardisation. Swords may have been produced to order by few and centralised production units. Finally, the disruption phase (900–800 BC) sees the development of many different chaînes opératoires at the same time as a typological diversification. This matches a nuclearization of the production units linked to the emergence of new groups of users.

Keywords: Bronze Age, metallurgy, material culture, weaponry, *chaîne opératoire*, techno-typology

Résumé : L'étude de l'organisation de la production métallique de l'âge du Bronze est particulièrement complexe en raison de la rareté des traces archéologiques directement liées à cette activité. Les vestiges liés aux ateliers sont en effet extrêmement ténus et ceux-ci sont généralement connus de manière indirecte, grâce aux déchets (fragments de moules, restes métalliques etc.) provenant de fosses situées à proximité. À cela s'ajoute la rareté des moules en contexte funéraire, qui ne permet pas d'identifier les sépultures d'artisans métallurgistes. Ces artisans et leur organisation restent ainsi largement méconnus. Afin de pallier ce manque de données, l'étude indirecte des métallurgistes à travers les objets qu'ils ont produits est une solution. La production d'un même type d'objet peut en effet être réalisée de différentes manières, avec des choix différents pouvant être opérés à chaque étape de la chaîne opératoire. Ces choix reflètent la manière de faire de l'artisan, qui dépend de sa créativité personnelle, des caractéristiques de l'objet à produire, mais aussi du contexte socio-culturel dans lequel il évolue, avec par exemple l'influence de son apprentissage et des contacts avec d'autres artisans : c'est l'habitus. L'influence de facteurs socio-culturels sur les choix techniques faits par les artisans métallurgistes rend possible l'identification de groupes de production, c'est-à-dire de groupes de producteurs partageant les mêmes techniques et savoir-faire, grâce à l'identification de choix communs aux mêmes étapes de la chaîne opératoire. Sans présager des liens ou de la structure de ces groupes, ces choix communs suggèrent que ces artisans partagent un même habitus et peuvent donc évoluer dans des contextes culturels proches. L'étude des techniques de production à partir des produits finis peut donc apporter de précieux éléments afin de restituer l'organisation socio-économique de la production métallique protohistorique. Un récent travail de thèse par l'auteur propose une synthèse sur les techniques de production des épées à poignée métallique de l'âge du Bronze en Europe, qui permet de renouveler nos connaissances sur les artisans à l'origine de ces armes (Dumont, 2022). Cette contribution vise à rendre compte des principaux résultats de ce travail doctoral. L'étude des techniques de production des épées à poignée métallique de l'âge du Bronze ne peut se faire par le seul examen de surface. Les artisans se sont en effet efforcés d'effacer la majeure partie des stigmates issus du processus de fabrication. Des méthodes non invasives d'imagerie par rayons X ont donc été employées. En compilant les études déjà publiées employant ces méthodes et en réalisant

des examens inédits sur des armes provenant de France, de Belgique et des Pays-Bas, quelque 634 épées ont livré des données technologiques sur les 2588 recensées en Europe. Ces données ont été employées pour l'élaboration d'une techno-typologie, c'est-à-dire d'une classification fondée uniquement sur des caractéristiques technologiques. Dix types techniques ont ainsi été identifiés. L'objectif était d'identifier les principales chaînes opératoires employées à l'échelle de l'Europe, durant toute la période. Ce nouvel outil offre un baromètre permettant d'évaluer la variabilité des techniques de production dans le temps et dans l'espace.
Trois phases sont ainsi identifiées dans la production des épées à poignée métallique de l'âge du Bronze. La première phase est celle d'expérimentation. Il s'agit de la période durant laquelle les épées à poignée métallique apparaissent et commencent à gagner l'ensemble de l'Europe, entre le Bz A2 et le Bz B (1800-1450 av. J.-C.). Bien que les données technologiques manquent pour pouvoir correctement évaluer la diversité des chaînes opératoires à cette période, il semble exister une importante diversité, tant technique que stylistique. Cette hétérogénéité traduit vraisemblablement l'existence de multiples petites unités de production, fabriquant des épées à petite échelle, peut-être sur commande.
La deuxième phase, dite de monopole, s'étend du Bz C au Ha B1 (1450-900 av. J.-C.). Elle se différencie de la phase précédente par le développement d'une nouvelle chaîne opératoire, appelée « principe de l'épée à fusée octogonale » (Achtkantschwert-Prinzip), qui s'impose en Europe centrale. Durant plus de cinq siècles, la quasi-totalité des épées à poignée métallique découvertes entre la zone nord-alpine et le bassin des Carpates sont produites de la même manière. Cette technique concerne exclusivement les épées de la tradition nord-alpine, formées des épées à fusée octogonale (Bz C), du type Riegsee (Bz D), à fusée à trois bourrelets (Ha A) et enfin à pommeau en coupelle (Ha B1). Malgré les évolutions stylistiques au cours du temps, la forme générale de la poignée change peu, tout comme son importante ornementation qui reste cohérente. En dépit de cette apparente standardisation, toutes sont des pièces uniques, individualisées par leur ornementation. Cette homogénéité technologique traduit une centralisation de la production au sein d'un même groupe de production. L'individualisation des productions pourrait correspondre à un système de fabrication à la demande et sur mesure. Finalement l'existence de copies montre que ces épées n'étaient pas accessibles à tous. Il pourrait ainsi s'agir d'un système de production contrôlée par un groupe social.
Finalement, la situation change abruptement durant le Ha B2/3 (900-800 av. J.-C.) : il s'agit de la phase de rupture. Si le principe de l'épée à fusée octogonale ne disparaît pas, il semble devenir marginal avec le développement de multiples nouvelles chaînes opératoires qui coexistent. Ces bouleversements technologiques s'accompagnent d'une diversification typologique ainsi que de changements dans la répartition des épées à poignée métallique. Il semble ainsi émerger de nouveaux groupes de production, peut-être en lien avec de nouveaux utilisateurs, dans ce qui semble être un contexte d'ouverture de la production et de l'utilisation de ces épées.

Mots-clés : âge du Bronze, métallurgie, culture matérielle, armement chaîne opératoire, techno-typologie.

Studying Bronze Age metalworkers and their organisation is a challenging task. Archaeological traces left by craftspeople producing bronze artefacts are indeed very scarce. First, very few metallurgy-related tools have been found in funerary contexts during the Bronze Age at a European scale (Nessel, 2013; 2019; Jockenhövel, 2018). Even when such tools were discovered in graves, the interpretation of the context regarding the activity of the deceased is extremely difficult (Molloy and Mödlinger, 2020, p. 173–176). Tools can also exceptionally come from so-called 'tool hoards' interpreted as the toolkits of a metalworker or a workshop, like the hoards from Génelard, France (Thevenot, 1998) and Murnau, Germany (Nessel, 2023). Yet, like graves, the interpretation of tool hoards is difficult. Indeed, these assemblages could be the result of a selection made within one or several workshops across a short or long period of time. They may therefore not be good representations of metalworker's organisation and know-how. Metalworkers are therefore almost completely anonymous for this period.

Furthermore, direct archaeological evidence of metallurgical activities is also rare (Molloy and Mödlinger, 2020, p. 183–184). Very few metallurgical workshops were excavated and well documented. The recently excavated workshops discovered in Montélimar (France) shows how tenuous the archaeological traces of this type of activity can be. The workshop was only detected thanks to the good preservation of Bronze Age ground layers and through the distribution of bronze artefacts production wastes (Cousseran-Néré et al., 2023; see also Mélin and Néré in this volume). If the ground layers were not preserved, there would have been almost nothing left for archaeologists to identify a workshop in this location. Remains and waste of metallurgical activities indicating the existence of workshops are usually discovered not in the workshop itself but in neighbouring waste pits. This way, many production sites have been identified in the British Islands (Adams et al., 2020) as well as in Scandinavia (Jantzen, 2008) thanks to the large number of clay moulds fragments (e.g. Mörtz, 2019). Depending on the good preservation of the metallurgical wastes, these sites can provide an overview of the different objects that were produced as well as a good documentation of the *chaîne opératoire*. This is for example the case with the fragments of moulds linked to a Late Bronze Age workshop in Aubervilliers (France), where pins and sword chapes were produced using clay moulds (Mélin et al. 2020; Mélin and Nerré, this volume). Archaeological traces of Bronze Age metallurgy therefore essentially consist in secondary contexts, whereas the actual workshops, i.e. the space where metalworkers were producing bronze artefacts, is usually missing. Addressing issues regarding the socio-economic organisation of production (seasonality, mobility, scale, level of specialisation etc.) is therefore complicated if not impossible.

Considering the lack of direct archaeological evidence left by Bronze Age metalworkers, studying them indirectly through the artefacts they manufactured can provide valuable inputs regarding the context of the production and its organisation. The manufacture of bronze artefacts can indeed involve many different techniques at each step of the *chaîne opératoire*. An important technological variability is often observed, sometimes within one type of object and within one region or period (e.g. Schwenzer, 2004; Kienlin, 2008; Nordez, 2019). This variability is related to technological choices made by metalworkers. This way of making bronze objects vary according to the metalworkers' *habitus*. This means that technological choices are not only a matter of personal choices but are also determined by the societies and the communities crafters belong to (Mauss, 1936; Nørgaard, 2018, p. 255–265). It means that technological choices are not only made based on the characteristics of the manufactured artefacts but are also influenced by socio-cultural factors (Latour, 1992; Lemonnier, 1993). This variability can therefore be used to identify different production groups, i.e. "a number of producers sharing a technology […] without suggesting their relative independence from one another or implying the size or structure of the work group" (Costin, 1991, p. 33).

The identification of production groups is an essential step to investigate the organisation of production of Bronze Age metalwork. By comparing types defined using stylistic features and different *chaînes opératoires* matching different production group, it would be possible to develop a better understanding of the relations between production groups and communities using bronze artefacts. For example, identifying different *chaînes opératoires* within a single type of artefact would show that different production groups and probably different workshops were involved in the production of objects sharing similar stylistic features. Similarly, different types of objects produced with the same technological choices would indicate that production groups were able to adapt their production to match different styles and possibly different groups of users. Combining stylistic and technological investigation would therefore result in a better understanding of the organisation of production, also providing useful models to understand the relations between metalworkers and users, which is essential to study the modes of diffusion of bronze artefacts.

If the stylistic evolution of Bronze Age metalwork has been studied extensively since the end of the 19th century, large-scale and in-depth technological studies beyond a few artefacts remain relatively scarce (Schwenzer, 2004; Kienlin, 2008; Mödlinger, 2011; Lagarde-Cardona 2012; Bunnefeld, 2016; Nørgaard, 2018; Nordez, 2019; Adams et al., 2020; Iaia and Dolfini, 2021). A recent PhD dissertation provides new insights into the production of Bronze Age solid-hilted swords using X-ray imaging techniques (Dumont, 2022). This new study gives an overview of the evolution of production groups manufacturing solid-hilted swords throughout Bronze Age at a European scale. After presenting the state of the art on Bronze Age solid-hilted swords, the methods used to investigate production techniques and the *chaînes opératoires*, this article will introduce the main results of the dissertation regarding the organisation of production.

STATE OF THE ART

Typochronology

Bronze Age solid-hilted swords have been extensively studied since the end of the 19th century. Because of their overall good state of preservation, the diverse shapes and ornaments as well as their unequivocal identification, they have been valued by private collectors and early museums, and therefore by scholars interested in archaeology (Dumont, 2022, p. 27–30). Research on Bronze Age swords took a turn at the beginning of the 20th century, when archaeologists, especially in Germany, started systematic typological studies (e.g. Naue, 1903). This typological approach was dominant for most of the 20th century, with a strong focus on stylistic features. Ernst Sprockhoff was among the firsts to also develop a geographic approach. By producing lists and distribution maps for every type he identified, he tried to understand the connections between different regions during the Bronze Age at a European scale (Sprockhoff, 1931; 1934). To that end, he tried to identify the geographic origin of a type (*Heimat*, Sprockhoff, 1930, p. VIII) by making a relation between the geographic concentrations observed on distribution maps and the supposed production centres.

Sprockhoff's approach combining a typological classification based on stylistic features and distribution maps to identify the regions where workshops were located has been extensively used in archaeological literature until now. It is mainly based on two assumptions that are usually not explicitly mentioned. Sprockhoff's first assumption correlates spatial concentrations of artefacts of one type and the regions where it was produced. This is a misinterpretation of distribution maps, which only show where artefacts were abandoned and found. Distribution patterns are indeed influenced by the state of research in different areas, the preservation of the artefacts that can vary according to the environment, and the selection operated by Bronze Age populations in the artefacts placed in different contexts (Stjernquist, 1967; 1970; 1985). Even if the areas where artefacts were used could be determined from distribution map, there is still an important gap to identify production centres. In the Bronze Age, production and consumption areas are indeed not necessarily the same, as suggested by the discovery of moulds sometimes far from the concentrations of objects they were used to produce (e.g. Gambari et al., 2007; Nordez, 2019, p. 59; Lachenal, 2022).

The second assumption is that the productions of different workshops can be identified using the morphological and decorative variability of the objects. It assumes that metalworkers are in total control of the aspect of the artefacts they produce. For Bronze Age Europe, our knowledge of the organisation of production doesn't allow for a precise identification of the participants in the decision process leading to the adoption of certain shapes and ornaments. Craftspeople could be the only ones deciding but the end users could also be involved, for example with 'attached specialists' producing upon command and sponsored by an elite controlling a part or the whole production (Costin, 1991, p. 11–13).

Although the relevance of this approach for identifying production centres has been criticised (Eggers, 1951, p. 23–27; Torbrügge, 1965, p. 75–79, 91; Neipert, 2006, p. 24–27), it remained widely used after the second World War. This methodology has usually been used implicitly, as the connection between typology, distribution patterns and production centres was probably considered trivial (Holste, 1953; Cowen, 1955; Müller-Karpe, 1961). H. Ottenjann is one of few explicitly stating that variations in decorations and distribution maps could be used to locate production areas (*Werkstattkreise*; Ottenjann, 1969). The exact same model has remained widely used in most publications, for example in the framework of the *Prähistorische Bronzefunde* series and beyond (e.g. Schauer, 1971, p. 181; Kemenczei, 1991, p. 36; Harding, 1995, p. 67; Quillfeldt, 1995, p. 197; Stockhammer, 2004, p. 100; Wüstemann, 2004, p. 78, etc.).

Although there is an abundant literature on Bronze Age solid-hilted swords, there is a striking lack of reflection about the significance of typological classifications regarding the organisation of production and the diffusion of artefacts. For these matters, studying production techniques seem to have more potential. There is indeed no doubt the production of swords was made by specialists, meaning technological choices are made by craftspeople alone, whereas this is not certain when it comes to stylistic features (see above).

Production techniques

Yet, production techniques have received far less attention than shapes and ornaments used to build typological classifications. The first technological investigations were performed in Germany at the end of the 1950s and during the 1960s with the development of X-ray radiography in archaeology (e.g. Drescher, 1958; Driehaus, 1959; 1961; Hundt, 1962; 1965). Most studies concern one or a few objects. Publications are therefore mostly descriptive, illustrating the potential of this new method. H. J. Hundt (1965) is the only one who tried to summarise the results of the X-ray examinations performed at the Römisch-Germanisches Zentralmuseum (Mainz, Germany). He identified different technological traditions in the production of Bronze Age solid-hilted swords and was one of the first to create a techno-chronology to summarise the evolution of techniques for a type of bronze object.

However, this trend to investigate production techniques using X-rays did not last very long. After the 1960s, D. Ankner is one of the only one publishing results of X-ray investigations on Bronze Age swords in line with H. J. Hundt (Ankner, 1977). This method was also not used much outside Germany. J.-P. Mohen installed a radiography device at the Musée des Antiquités Nationales, which was occasionally used to investigate bronze artefacts (Mohen, 1970; 1971; 1973). This was also the case in Switzerland where V. Rychner also investigated some artefacts, including a few Bronze Age swords (Rychner, 1977; 1987). Despite the potential offered by this new technique for investigating production techniques, it was never deployed at a large scale and remained only used for a few case studies. The trend initiated in Germany rapidly declined as other methods, especially elemental and isotopic analyses, grown in popularity from the 1980s onwards.

Since the early 2000s, we observe a renewed interest for imaging technique for investigating production techniques, especially for complex artefacts such as solid-hilted daggers (Schwenzer, 2004) and swords (Bunnefeld and Schwenzer, 2011; Mödlinger, 2011; Bunnefeld, 2016). This is correlated with the development of new techniques such as computed tomography (CT-scan), which enables the 3D reconstruction of the object's structure using X-rays. This is a powerful tool for investigating the *chaînes opératoires* of complex artefacts formed of several elements fixed together using different techniques, like swords (Mödlinger, 2008; Dumont et al., 2020; 2021). These new studies provide information on the manufacture of swords in northern (Bunnefeld, 2016) and central Europe (Mödlinger, 2011). The goal of my dissertation was to investigate western European swords in order to fill this gap in the history of research and then propose an overview of the production techniques and their variations in time and space at a European scale (Dumont, 2022).

METHODS

Surface observations

The technological investigation starts with the observation of the objects' surfaces. On some artefacts, traces of the production process can indeed remain visible. This is for example the case of the Late Bronze Age antenna swords from the Vénat (France) hoard (fig. 1), one of the biggest Bronze Age hoard discovered in France (Coffyn et al., 1981). The hilt of this sword shows important porosity with many blow holes visible on the surface, resulting from gas trapped in the bronze during the casting. There are also several breaches in the bronze structure showing it was not cast in one piece but rather in at least four steps, each casting being made on the top of the previous one. This technique is known as over casting or secondary casting. The surface of the pommel also carries information regarding the casting technique. The rim around the holes close to one of the antennae as well as the transition between the two castings of the pommel suggest they were made using lost-wax casting.

However, the sword from Vénat is an exception. The important porosity indicates the sword may be a miscast, selected to be abandoned in the hoard rather than to be melted down, although the cutting edges seem to have

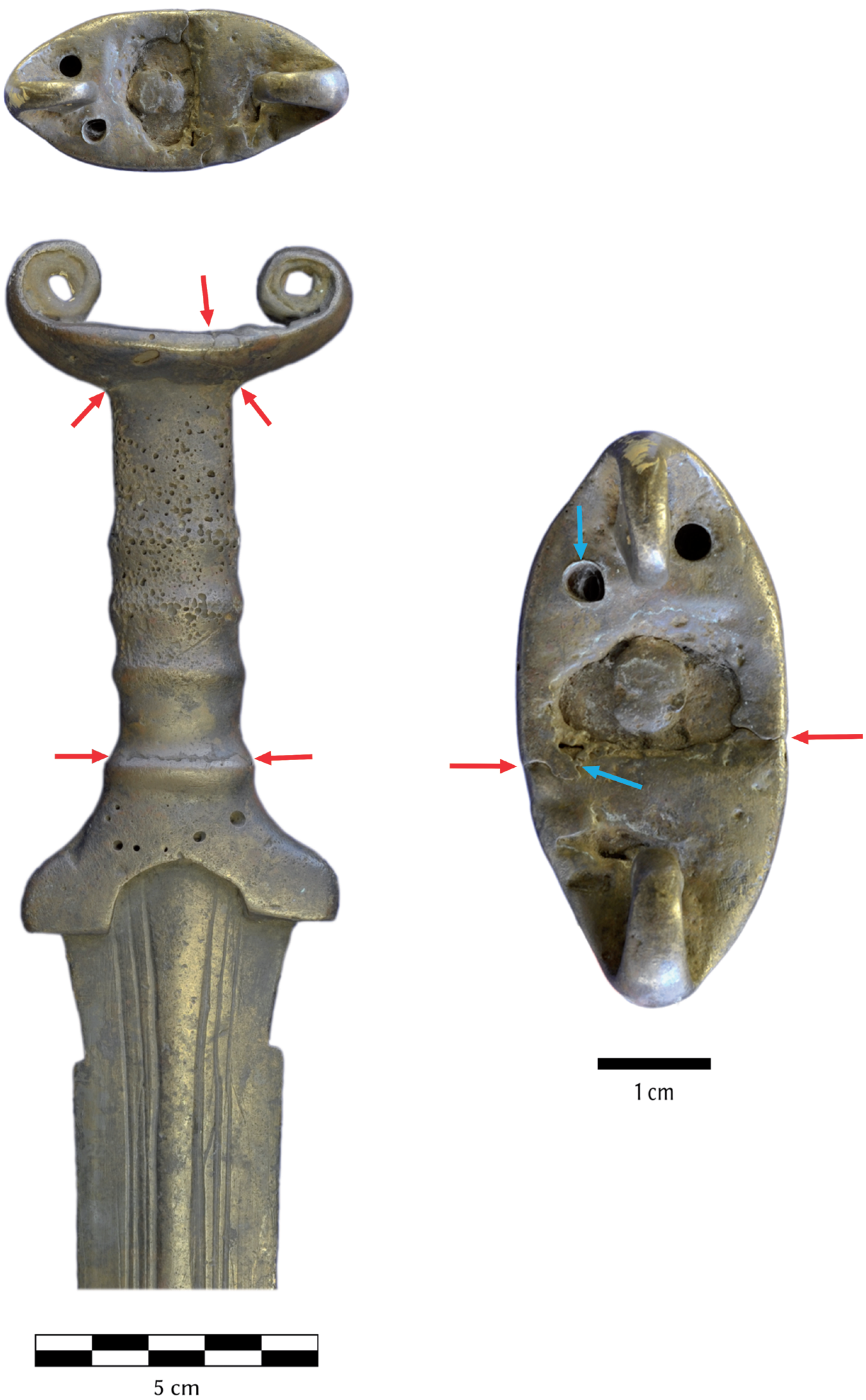

Fig. 1 – Hilt of the antennae sword from Vénat (Saint-Yrieix-sur-Charente, France). Red arrows indicate breaks in the hilt resulting from multiple castings. Blue arrows points at the traces of wax working on the pommel. © L. Dumont..

been sharpened. Although casting mistakes are precious for understanding casting techniques, they are scarcely discovered. Most Bronze Age solid-hilted swords were carefully crafted and finished, erasing most of the traces from the production process. There are therefore less traces visible compared to other types of bronze objects with a rougher finish, such as axe heads (Kuijpers, 2017). The ornamentation patterns can also be used to investigate production techniques (e.g. Berger, 2012; Nørgaard, 2018), but most swords found in Western Europe are undecorated.

We must therefore find other ways to reconstruct the *chaînes opératoires* and identify different technological choices revealing the different production groups behind the manufacture of Bronze Age solid-hilted swords. Invasive methods, such as metallographic analyses giving information on post-casting treatments (e.g. Kienlin, 2008; Kuijpers, 2017), or elemental as well as isotopic analyses (e.g. Mödlinger, 2011; Ling et al., 2019;

Mödlinger et al., 2021), were ruled out considering the difficulty to sample such precious artefacts. We rather chose to focus on non-invasive X-ray imaging techniques to investigate the casting and fixation techniques used to manufacture solid-hilted swords.

Radiography

Radiography is based on the ability of X-rays to pass through the matter. X-rays are light, it is therefore possible to use them to produce images, either with an analog film or a detector producing a digital image. As X-rays are attenuated according to the materials they go through and their thickness, the exposition of the film or detector varies. It produces a grayscale image with variations in the grey intensity reflecting the structure of the investigated artefacts. As it is widely used in different context (medicine, industry, heritage etc.), it is the most accessible technique to investigate production techniques in a non-invasive way. It is indeed relatively cheap, and it is easy to find a laboratory to perform this type of analysis, whether it is specialised in heritage applications or not.

Despite the advantages and potential of this method for reconstructing the *chaînes opératoires* of Bronze Age metalwork, it also has limits, especially in the case of very complex artefacts formed of several elements fixed using different techniques. As the images produced using X-rays are in two dimensions, several overlapping elements can produce images that are very complicated to interpret. This is the case of the Late Bronze Age Auvernier sword from L'Épineuse (Vénarey-lès-Laumes, France). The X-ray (fig. 2) of the lower part of the hilt is easy to interpret: we clearly see the outline of the tang, the part of the blade the hilt is fixed on, and the hilt completely includes it without any room between both parts. The outline of the tang remains visible, and many pores are located at the interface, meaning that the hilt was produced by secondary casting directly on the top of the tang. The upper part of the hilt is more complex, making the interpretation more complicated. There seems to be a shallow part in the central part of the hilt with two rivets, the depression being covered by a thin sheet of bronze. Although nothing is visible on the surface, there are breaks in the metal visible on the X-ray suggesting the upper part of the hilt involved multiple castings. First, the upper part of the grip was cast over the lower part. It is hollow in its centre and a trapezoidal bronze piece seems to be inserted in it. The lower part of the pommel was then cast over the grip. The upper part of the pommel was probably cast separately and fixed on the top of an organic piece that is no longer preserved. The fixation seems to be made with two short bronze rods on each side of the pommel. An explanatory drawing regarding the interpretation of the X-ray is provided on fig. 2. This interpretation remains hypothetic as the 2D image resulting

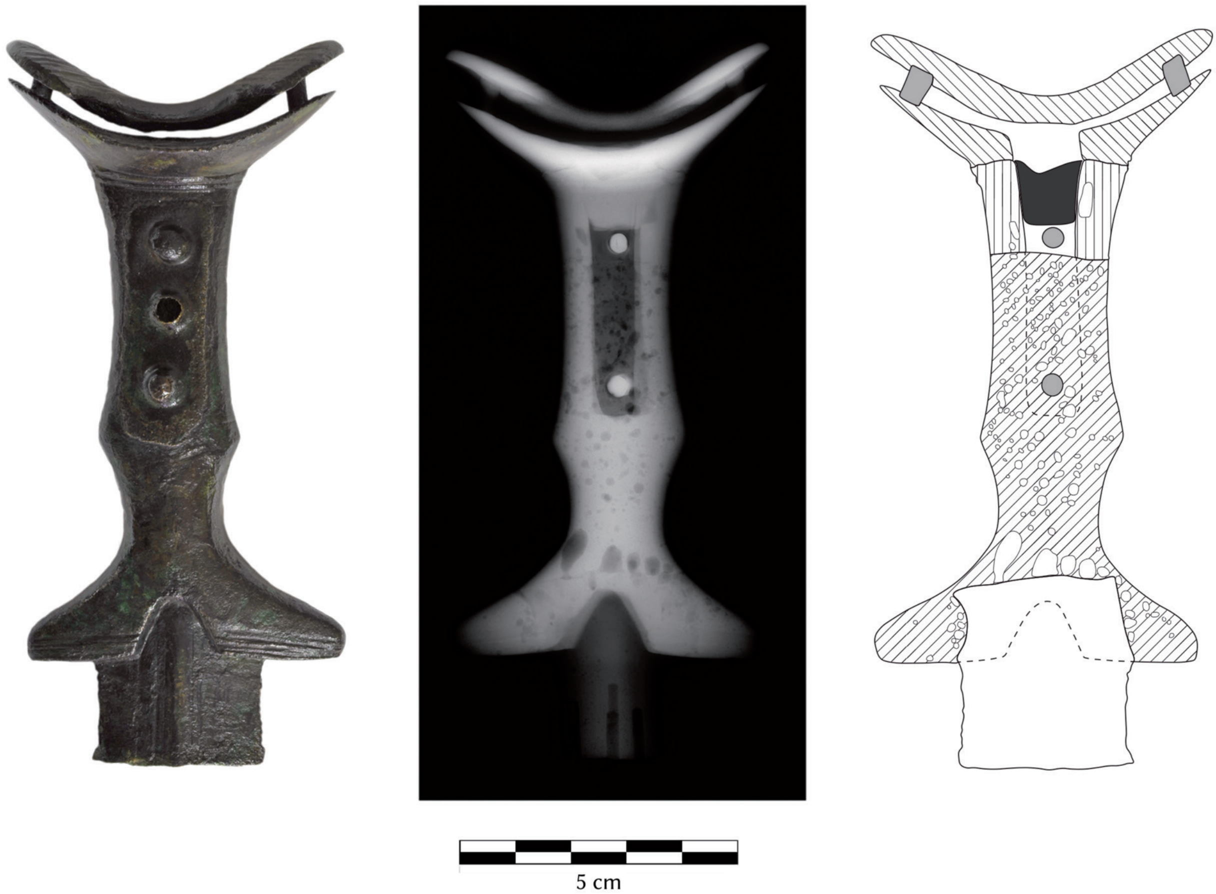

Fig. 2 – X-ray of the L'Épineuse sword's hilt (Vénarey-lès-Laumes, France). © E. Lambert, L. Dumont.

from the radiography doesn't allow for a clear understanding of the upper structure of the hilt.

CT-scan

CT-scan is an X-ray-based imaging technique relying on digital radiography to produce a 3D reconstruction of the investigated samples, including their inner structure. It consists in performing multiple X-rays of the same object, which is each time slightly rotated. By collecting multiple projections of one artefact under different angles, it is possible to reconstruct cross-sections. By stacking them up, the volume and structure can be digitally reconstructed in a totally non-invasive way. For investigating solid-hilted swords production techniques, we used high-resolution computed tomography (µCT) of the hilt area, mostly at Ghent University Centre for X-ray Tomography (UGCT). µCTs were performed using the HECTOR (High Energy CT Optimised for Research) setup (Masschaele et al., 2013). It is equipped with a X-ray WorX XWT 240-SE microfocus source which was operated at 220 kV and 60 W. A 1 mm copper filter was placed on the X-rays source to minimize beam hardening artefacts. 1,401 or 1,501 projections were acquired with a 1s acquisition time on a Varex XRD 4343 flat panel detector with a 2,880 × 2,880 pixel matrix or on a PerkinElmer 1620 CN3 CS flat panel detector with a 2,024 × 2,024 pixel matrix, enabling a reconstruction with an average voxel size of 80 µm.

CT-scan allows for a non-invasive technological investigation by revealing the hilt structure in two and three dimensions. It provides information regarding the casting of this part, its quality and the fixation technique(s) used to fix the hilt to the blade. One of the swords found in the Rhône river in Grigny (Rhône, France) shows the potential of this technique (fig. 3). The 2D cross-sections show the hilt was cast over the tang, whose outline remains visible. It also shows hollow parts on the central part of the grip and within the pommel that were not visible from the outside, probably filled by corrosion products. It shows this hilt was originally made by a combination of bronze and organic materials inlayed in the grip and the pommel. They are not preserved anymore but CT-scan clearly shows the difference between uncorroded bronze and corrosion products, revealing the structure of the hilt invisible from the surface. CT-scan can also be used to visualize hidden surface, like the surface of the tang

Fig. 3 – Photo and CT-scan of the hilt of a sword from Grigny (France). © I. Josipovic, L. Dumont.

located under the hilt, which can carry production traces or even counting marks left by the metalworker (Dumont et al., 2021).

CHAÎNES OPÉRATOIRES

Techno-typology

Using the different methods presented above allows for the identification of different *chaînes opératoires* corresponding to different technological choices made in the manufacture of Bronze Age solid-hilted swords. To that end, a techno-typological framework was created (fig. 4) based on 634 swords investigated using X-ray imaging techniques, out of 2588 listed in Europe (Dumont, 2024). This classification framework consists in three main types of swords, according to the type of hilts they are equipped with: full (EPP), hollow (EPC) or with a flanged tang framed with bronze pieces (ELCM). There are also semi-metallic hilts whose structure is made partly of bronze and partly of organic materials (type EPSM) which will not be discussed in this article as they are scarce and mostly limited to northern Europe.

Methods used for investigating production techniques do not allow for the identification of many different *chaînes opératoires* for full hilts (EPP). They are simply divided in two types: the ones cast in one piece with the blade (EPP1) and the ones produced by secondary casting over the tang (EPP2). X-ray based imaging technique enable the identification of a stronger technological diversity for hollow-hilted swords (EPC). Two features are used to identify technological types. The first is the shape of the hollow part of the hilt, which depends on the core it was cast on (see below). This core can replicate the shape of the hilt (EPC1) or the shape of the tang of the blade it is associated to (EPC2) or be independent (EPC3). The second feature is the shape of the tang, which influences the way the hilt is fixed to the blade. The tang can be short (inserted only inside the guard), bipartite (inserted inside the guard and the grip) or rod-like (narrow tang going all the way through the hilt from the guard until the pommel). This classification therefore takes into account the design of the hilt, how it is cast and how it is fixed to the blade. As only 5 swords belong to the ELCM type, characterized by a flanged tang framed with bronze pieces (Dumont, 2024), no further divisions were made.

Of course, other features may have been included in this classification frameworks. Some of them were deliberately excluded, such as the number of rivets, which can vary during the life of the object, for example if it had to be repaired. The goal of the techno-typology is also to identify the main *chaînes opératoires* and technological variations at a European scale, and not to provide a systematic and comprehensive description of all techniques. Only features that could be well observed and understood using X-ray imaging techniques were therefore included.

Although we cannot provide here an in-depth description of every single technological type identified, we will describe below the main ones encountered in Europe and their principal features.

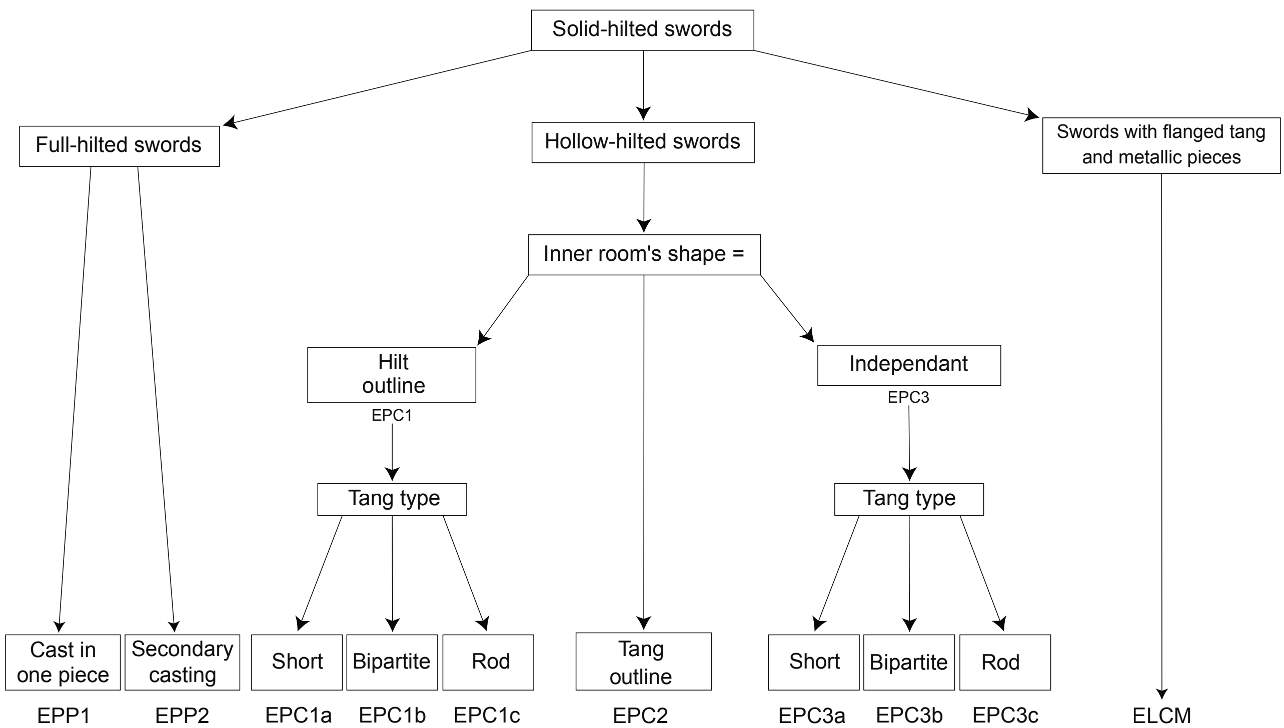

Fig. 4 – Technological classification framework of Bronze Age solid-hilted swords (Dumont, 2022).

Full hilt

Unlike hollow-hilted swords whose blade is inserted within the hilt by an opening at the base of the guard, swords equipped with a full bronze hilt are characterised by the absence of room within the hilt. These totally solid hilts can be achieved twofold: by casting the hilt and blade together as a single piece (type EPP1), or by casting the hilt directly over the tang of the blade (type EPP2). The first option is very uncommon among European Bronze Age solid-hilted swords. Only 6 swords produced this way are currently identified in Europe using X-ray imaging techniques. Most of them belong to the Prejmer type. These swords are known to be imitations of three-ribbed and cup-shaped pommel swords during Ha A and Ha B1 (ca. 1200–950 BC) and they are mostly found in eastern central Europe (Vachta, 2008; Novotná, 2014, p. 74).

Most full hilts are produced by secondary casting, meaning by casting the hilt directly over the top of the blade. This technique is easily identified as the outline of the tang over which the hilt is cast remains visible (figs. 2 and 3, see also infra fig. 6, EPP2). The temperature of the bronze as well as its quick cooldown after the casting does not allow for a weld between both parts. The fixation is therefore done by mechanical contact between the hilt and the tang. In some cases, notches or holes in the tang enable a strong fixation as the metal flows withing these parts, preventing any separation. In other cases, such features are not detected. Using a blade equipped with a short and narrow tang, this may lead to a weaker fixation. Porosity located at the interface between the hilt and the tang is also typical of this technique. When casting the hilt over the blade, the melted bronze gets in contact with the tang, producing a faster cooldown and solidification. Gas produced during the operation can then stay trapped within the metal. Secondary casting can be made using different types of mould. Permanent moulds, for example in stone or in bronze, can be used, but they require a perfect fit with the top of the blade. Lost-wax casting was probably widely used because of its versatility, as the wax model can be adapted to any kind of tang. However, X-ray imaging techniques do not enable the identification of the precise casting technique. All swords with a secondary cast hilt are therefore included in type EPP2, although they may correspond to slightly different *chaînes opératoires*.

Hollow hilt

Swords equipped with a hollow hilt show a greater technological variability than the ones with full hilts as imaging techniques allow for a better characterisation of their production techniques. The choice was made to classify them according to two features: the shape of their hollow part, which depends on the way they were cast, and the shape of the tang they are fixed on, which influences the fixation techniques.

The production of hollow hilts is made with mould including a core. When bronze is poured inside the mould, it is filling the space between the core and the outer part(s). After the casting, the core is removed, leaving a hollow room inside the hilt. This type of casting over a core can be done using the lost-wax technique (fig. 5). It is also possible to use a mould made of stone or bronze, like the one from Erlingshofen (Germany, Bavaria). This reusable bronze mould is made of two parts each one with half the hilt imprint. When joined together, the shape of the hilt is complete and a bronze core is inserted between both parts (Overbeck, 2018, p. 81–82).

The shape of the core used during the casting and therefore the shape of the hollow part of the hilt is an important feature, as variations can be connected to different casting techniques and can have an effect on the way the hilt is fixed to the blade. If the shape of the core reproduces the outline of the hilt (type EPC1), it is usually wider in central part of the grip or in the pommel than at its base (fig. 6, EPC1a, EPC1c). This means the core cannot be removed and reused after the casting, unlike the Erlingshofen mould. A single use core, typically made of clay and destroyed after the casting, must therefore be used. On the contrary, when the core shape does not match the outline of the hilt nor the shape of the tang (type EPC3), it can simply be conical (fig. 6, EPC3b) and

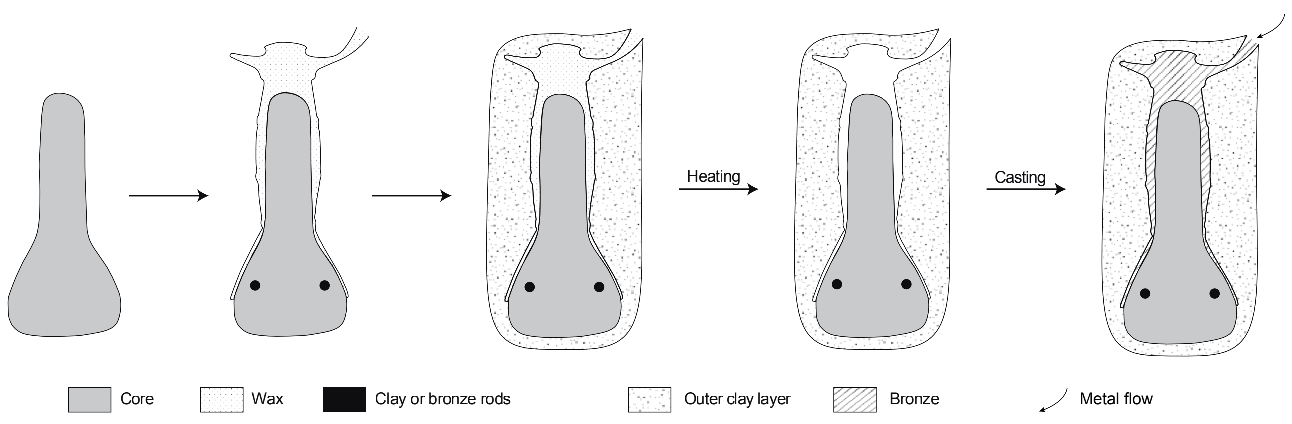

Fig. 5 – Main steps of the production of a hollow hilt by lost-wax casting. © L. Dumont.

reused for multiple castings. Finally, the hollow part of the hilt can also exceptionally match the shape of the tang (fig. 6, EPC2). In that case (type EPC2), the hilt needs to match one specific blade, whereas types EPC1 and EPC2 are more versatile as they can match different types of blades.

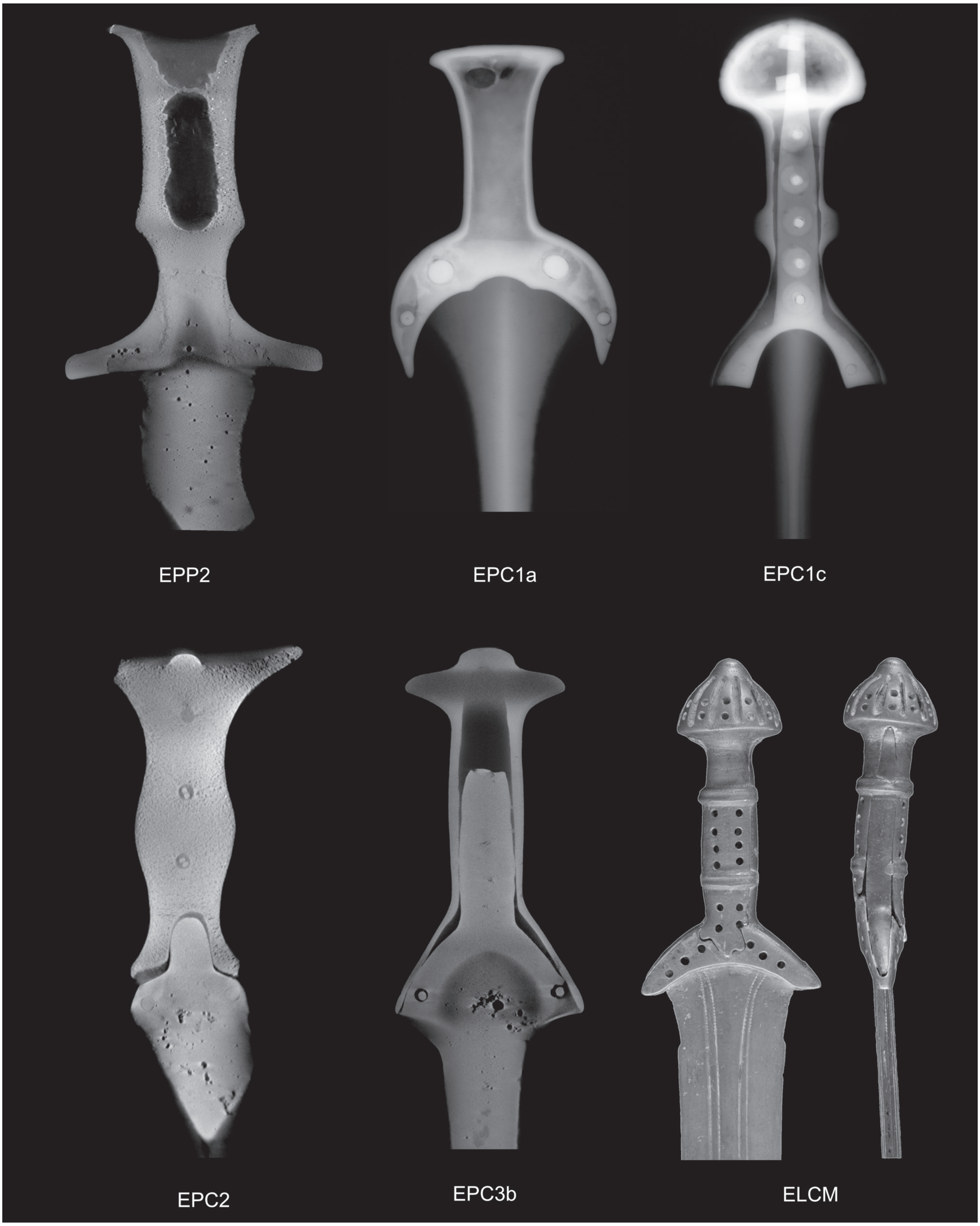

Fig. 6 – Overview of the main technological types of Bronze Age solid-hilted swords. EPP2. Grigny (France), © I. Josipovic, L. Dumont. EPC1a. Mont-Saint-Aignan (France), © La Fabrique de Patrimoine en Normandie. EPC1c. Between Tournus and Farges (France), © E. Lambert. EPC2. Saint-Romain-en-Gal (France), © I. Josipovic, L. Dumont. EPC3b. Champagneux (France), © I. Josipovic, L. Dumont. ELCM. Montbellet (France), © L. Dumont.

For types EPC1 and EPC3, variations are identified based on the type of tang they are fixed on. Tangs can be either short, bipartite or rod-like. Short tangs are inserted only up to the guard of the hilt. This type of tang associated to a hollow hilt only allows for a fixation using rivets (fig. 6, EPC1a). Longer tangs inserted within the guard and the grip (bipartite) or all the way up until the pommel (rod-like) enable more complex techniques used for a stronger fixation. Rivets alone can still be used, but some swords are also equipped with a hilt fixed with no rivets, only by locking both elements together. The tang is in that case forced inside the hilt and the fixation is made by mechanical contact between the tang and the inner walls of the hilt. This contact can be made within the grip for bipartite tangs or within the pommel for rod-like tangs. Finally, these techniques can be combined. Some swords are made with a hilt first locked with the tang and then reinforced with rivets (fig. 6, EPC1c, EPC3b).

Flanged hilt and bronze pieces

The last type identified in the techno-typology includes a small group of swords (5 so far) characterized by a flanged hilt framed with bronze pieces (fig. 6, ELCM). This type of hilt is not designed as the hollow hilts. Instead of having a flat tang inserted inside the hilt by a slit at the base of the guard, they have flanged tangs with a hilt composed of one or several elements riveted on each side, with the sides of the tang remaining visible. This type of tang is mostly found in swords that used to be equipped with an organic hilt. This similarity suggests these swords are made with a blade initially designed for an organic hilt, and that a customized bronze hilt was made to replace it.

Although the 5 swords belonging to type ELCM are not found in the same regions, they share similar stylistic features, especially very typical perforations of the hilt that are not known among other types of solid-hilted swords. However, they are not all produced the same way. Most are made with a single bronze piece with a central slit in which the tang fits and is fixed with rivets. The sword from Montbellet (France, Saône-et-Loire) is designed differently: the hilt is composed of two pieces locked on the tang, requiring no rivets. Considering the differences in the distribution of these swords, their morphology and the techniques, they probably do not come from the same workshop. As they are all using a blade designed for an organic hilt, the similar decoration using perforations could be an imitation of ornaments commonly found in hilts made of wood or other organic materials.

Organic and bronze hilt

There are also a few swords whose hilt is composed both of bronze and organic elements. This category does not include swords with bronze hilt adorned with inlays of organic materials such as Auvernier and Tachlovice types swords. In this case, the organic elements are purely ornamental and do not play a functional role in the hilt structure. These swords, between solid-hilted and organic-hilted swords, are classified separately. The classification is simpler: four types are identified based on the way the bronze part of the hilt is fixed to the blade. It can be cast with the blade (type EPSM1), cast over it (type EPSM2), riveted (type EPSM3) or locked (type EPSM4).

ORGANISATION OF PRODUCTION

Experimentation phase

This technological classification of Bronze Age solid-hilted swords is a tool to evaluate the homogeneity or heterogeneity of the *chaînes opératoires* both in time and space. It provides a barometer to identify chronological and spatial variations in the organisation of production. Using this tool, three main phases are identified: the experimentation, 'monopoly' and disruption phases.

The experimentation phase matches the first development of solid-hilted swords in Bronze Age Europe starting at the 18th century BC (Schulz, 2004-2005). It is characterized by a technological and stylistic diversity and well-identified types, each of them comprising few swords. In eastern and northern Europe, most swords fit in the Hajdúsámson-Apa and Au-Valsømagle types (Bunnefeld, 2016, p. 19–20), which include several variants. In central Europe and especially in the northern Alpine region, the Spatzenhausen type appears during Bz B (Holste, 1953, p. 13–15). In western Europe, most solid-hilted swords belong to types Tréboul-Saint-Brandan and Le Cheylounet-Jugnes (Daugas and Vuaillat, 2009; Dumont 2022, p. 159–167).

Only the production techniques of the Le Cheylounet-Jugnes swords were properly investigated (Daugas and Vuaillat, 2009). They are all made in the same way and all belong to type EPC3a, with a hollow hilt fixed to a short-tanged blade using rivets. Apart from these swords, the available technological data regarding these early solid-hilted swords is very limited due to the lack of technological investigation using X-ray imaging techniques (fig. 7).

Yet, available images for these swords suggest different *chaînes opératoires* were used, hence a low technological standardisation. Spatzenhausen swords are commonly made with an opened pommel in its centre, matching the presence of an inner canal between the hilt's inner room and its surface (Hundt, 1965, p. 43), which could match a stand for keeping the core in place within the mould and removed after the casting (Schwenzer 2004, p. 147; Mödlinger, 2011, p. 32). Finally, although technological data lacks about Hajdúsámson-Apa swords, the existence of hilts fully made of bronze as well as composite ones with gold or organic pieces (Meller, 2010) gives an insight into their diversity.

This typological and technological diversity matches the existence of multiple production groups. Consider-

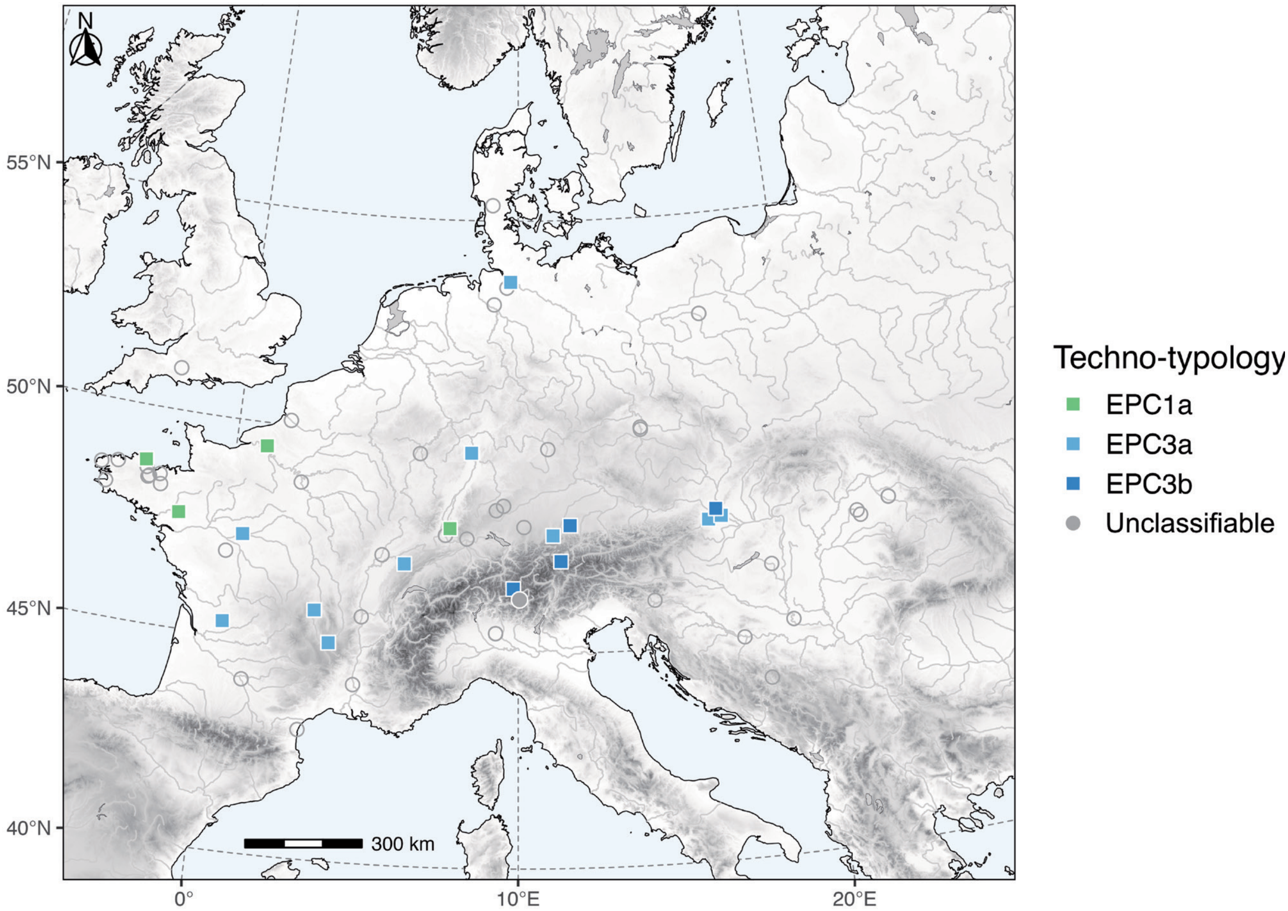

Fig. 7 – Distribution of solid-hilted swords during the experimentation phase (Bz A2-B, ca. 1800-1450 BC) according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

ing the few swords discovered (about 10 for each type, see Dumont, 2024), this probably corresponds to a small-scaled and versatile production units sporadically making swords among other types of objects. Although data is lacking to quantify it, the apparent technological diversity within Hajdúsámson-Apa and Au-Valsømagle swords (Bunnefeld, 2016, p. 45–48, p. 58–60) and the existence of peculiar techniques involving different materials (Meller, 2010) suggest different small and versatile production groups were involved in the production of swords, sometimes experimenting with techniques that were not subsequently used. In the absence of direct archaeological traces, workshops cannot be located. We must note that this technological creativity during the early stages of solid-hilted swords development is not associated to a low quality or sloppy production. On the contrary, investigated swords from the Le Cheylounet-Jugnes and Hajdúsámson-Apa types (Daugas and Vuaillat, 2009; Meller, 2010; Bunnefeld, 2016) show a very good casting quality with a low porosity and a good-quality fixation with up to 6 rivets. Craftspeople were therefore very careful in their work and a form of attached production with crafters producing swords in small quantities and made to order for sponsors of the craftspeople.

'Monopoly' phase

The situation changes abruptly in the middle of the 15th century BC (Bz C) with the introduction of a new type of sword in central Europe: the octagonal-hilted swords (*Achtkantschwerter*). Octagonal-hilted swords are named after the typical octagonal cross-section of their hilt (Quillfeldt, 1995, p. 45–93). Although the shape of the hilt and its ornamentation takes root in earlier types, such as swords of type Spatzenhausen (Hundt, 1962), they introduce a new technique to fix the hilt to the blade. The tang becomes longer compared to swords from Bz A and B: it is bipartite and reach the centre of the grip. Thanks to this shape, the fixation no longer only relies on rivets. The tang is first locked within the hollow hilt. It is forced inside it by making contact with the inner walls. Once both parts locked, the fixation is strengthened with two rivets on each side of the guard (fig. 6, EPC3b). This technique enables a strong fixation without multiplying the rivets. Using multiple rivets can indeed be challenging. The rivet holes need to be carefully positioned in the moulds, or they have to be drilled and perfectly aligned on the hilt and on the tang. The difficulty of the task increases with the number of rivets. This technique is known as the octagonal-hilted sword principle

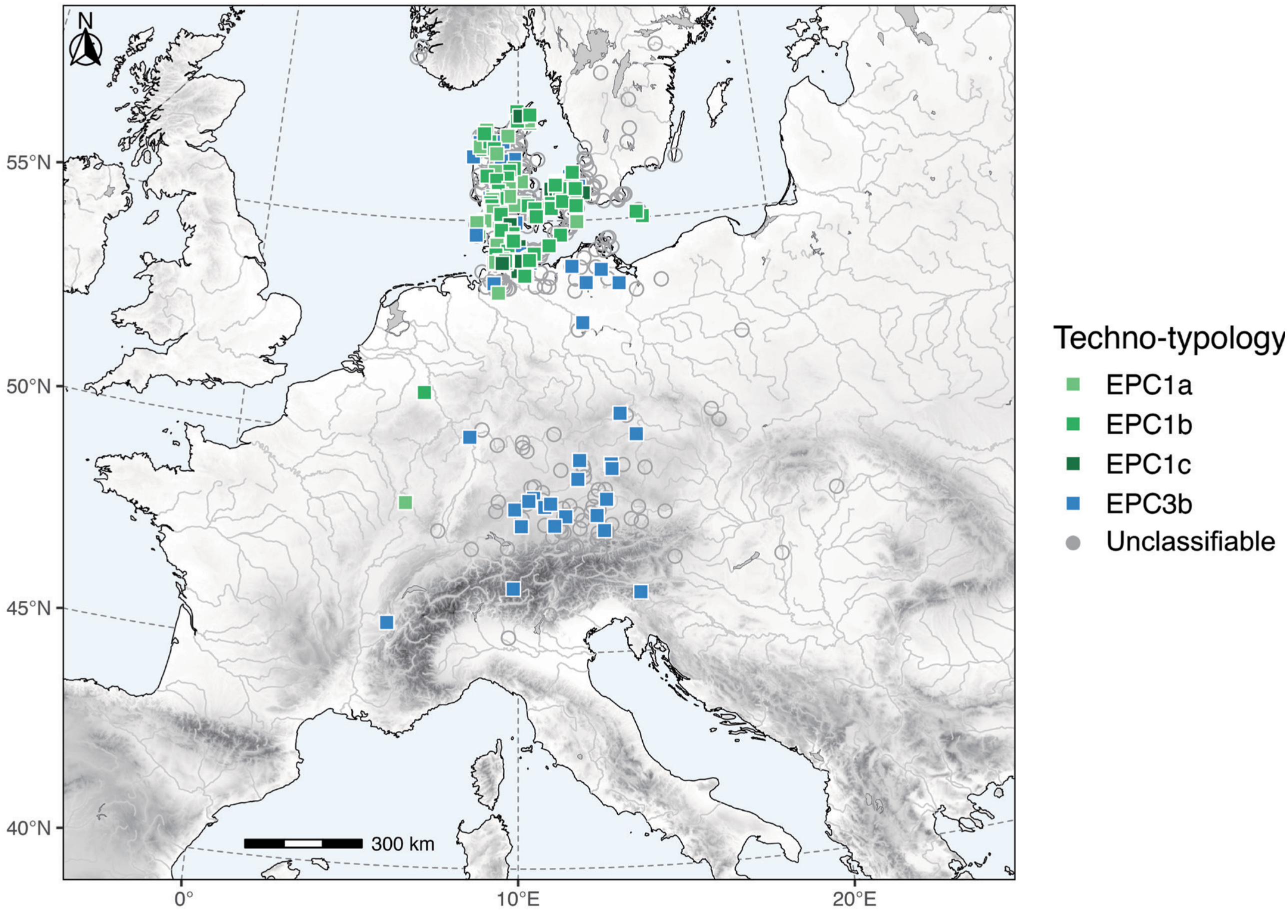

Fig. 8 – Distribution of Bz C (ca. 1450-1300 BC) and Period II (ca. 1500-1330 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

(*Achtkantschwert-Prinzip*, Hundt, 1965, p. 54). This new *chaîne opératoire* matches technological type EPC3b.

The development of the *Achtkantschwert-Prinzip* during Bz C marks the start of a new technological tradition, first in the north-alpine region and then in Central Europe. Most solid-hilted swords found in the north-alpine region and in the Carpathian Basin from Bronze C to Ha B1 (ca. 1450-900 BC) are produced in the same way (Dumont, 2022, 2024). Octagonal-hilted swords are found both in the North-Alpine region and in southern Scandinavia (fig. 8) Despite slight stylistic variations, all X-rayed Riegsee type swords (Bz D), three-ribbed swords (*Dreiwultschwerter*, Ha A) and swords with a cup-shaped pommel (*Schalenknaufschwerter*, Ha B1) belong to type EPC3b and were produced according to the *Achtkantschwert-Prinzip* (fig. 9). The technological standardisation is only valid for central Europe. In northern Europe, typical nordic swords are made with a bronze hilt with different shapes and ornaments as well as with different *chaînes opératoires*, including hollow-hilts cast over a core reproducing the hilt outline (types EPC1a-c, Bunnefeld, 2016; see here figs. 8-9). This *chaîne opératoire* combining a hollow hilt and a bipartite tang fixed by locking both parts and adding two rivets seems to have been considered as the most efficient or suitable for the production of swords. This strong technological consistency suggests a centralised production within a few workshops, probably operating in the same region. Over such a long period, a production scattered across many production units would have more chances to result in a diversification of the *chaînes opératoires*. In the total absence of moulds for casting this type of hilts, the production centre(s) cannot be located. It remains unclear whether blades were manufactured alongside hilts or if they were produced in different workshops. Although X-ray imaging techniques provide a good way of documenting the casting of the hilt and its fixation to the blade, it gives less information regarding the production of the latter.

Swords produced according the *Achtkantschwert-Prinzip* also forms a homogenous stylistic group. Although we observe slight variations in the shape and ornamentation of the hilt and the blade, the tang keeps the same shape, the outline of the hilt does not change much and the graphic ornamentation composed of thin engraved patterns covering the hilt surface remains consistent between Bz C and Ha B1. Except for octagonal-hilted swords, found both in the north-alpine region and in southern Scandinavia (Bunnefeld, 2014), swords of the North-Alpine tradition also share similar distribution patterns. They are usually found between the Rhine

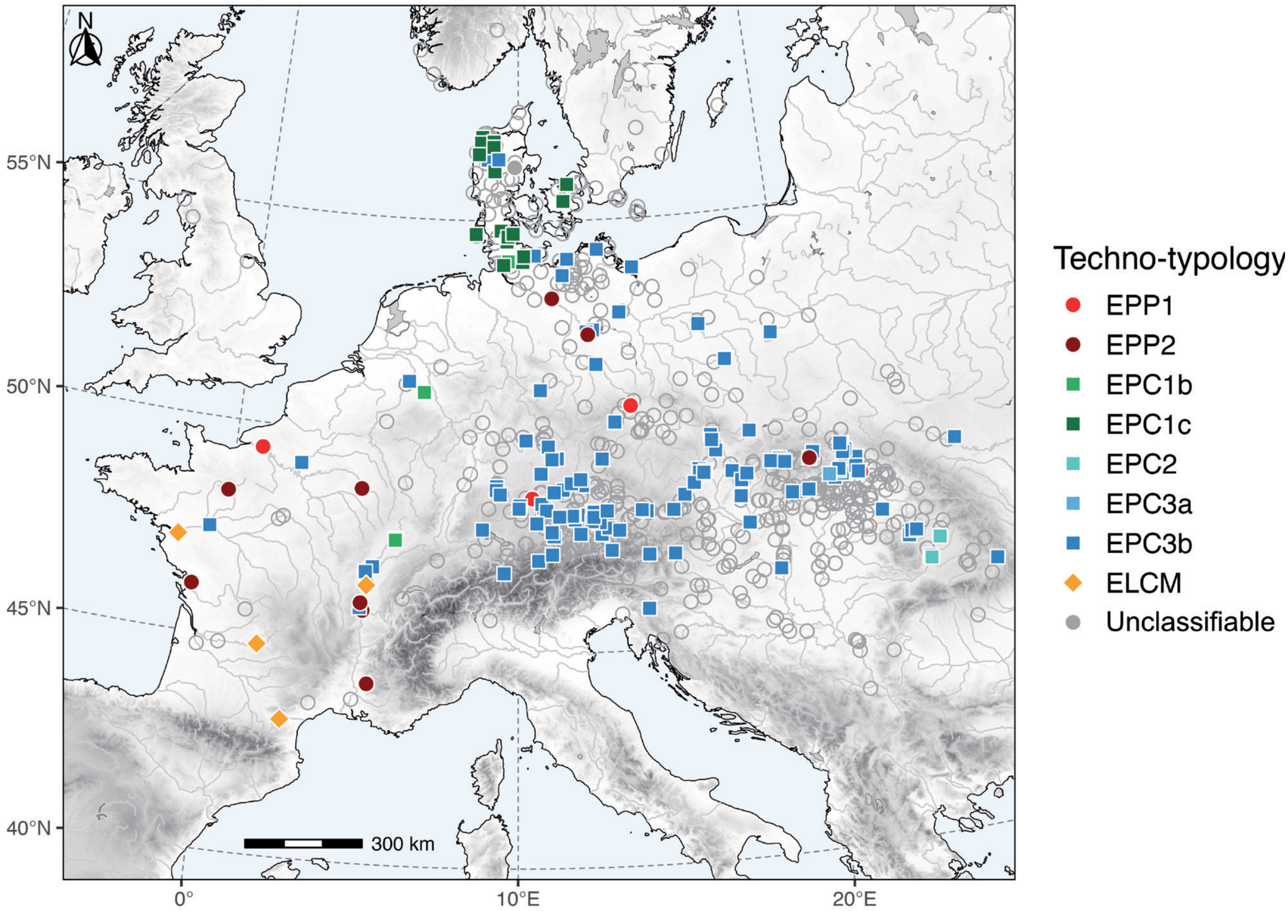

Fig. 9 – Distribution of Bz D to Ha B1 (ca. 1300-950 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

valley and the Carpathian Basin, alongside a west-east axis (fig. 9). This indicates a continuity in the consumption habits of the users of these swords, which do not seem to vary much regarding the continuity both in the style and deposition practices (Dumont, 2022, plates 111, 116, 125, 131).

Swords of the north-alpine tradition are manufactured following the same *chaîne opératoire* and share some stylistic features. Within one type, they can look a lot like each other. Yet, they are all unique. The individualisation is made through the ornamentation of the hilt, which makes each sword unique. They are therefore not mass produced. This unicity is probably achieved using lost-wax casting, which allows the production of relatively standardised wax models that can be individually decorated. This production could involve attached specialists manufacturing swords to order for their sponsors, who may have been involved in the choice of the ornamentation of the hilt. This could explain the technological homogeneity of octagonal-hilted swords found both in the north-alpine region and in southern Scandinavia (they all come from the same workshops) combined to the diversity of their ornamentation (sponsors in both regions do not share the same taste). In that scenario, the access to this kind of artefacts would be restricted to a category of the population, hence the existence of imitations, like the swords of type Prejmer (Vachta, 2008; Novotná, 2014, p. 74).

Disruption phase

The organisation of production changes abruptly at the end of the Bronze Age, during Ha B2/3 (ca 9th c. BC). This last period is characterised by a typological and technological diversification. Unlike the monopoly phase during which solid-hilted swords mostly belonged to a single type (e.g. swords with a cup-shaped pommel during Ha B1), several types co-existed during Ha B2/3. Most swords then belonged to types Mörigen, Auvernier, Tachlovice and to several types of antennae swords (Dumont, 2022, p. 248–304). Despite this apparent diversity, swords are more standardised. Whereas earlier solid-hilted swords were individualised through the ornamentation of the hilt, Ha B2/3 swords types are more homogenous as the graphic decoration is less important and the development of reusable moulds made of stone or bronze enabled serial production (Dumont, 2021).

This phase also saw the outbreak of multiple technological traditions and *chaînes opératoires* existing together in Europe (fig. 10), contrasting with the homogeneity and technological standardisation observed ear-

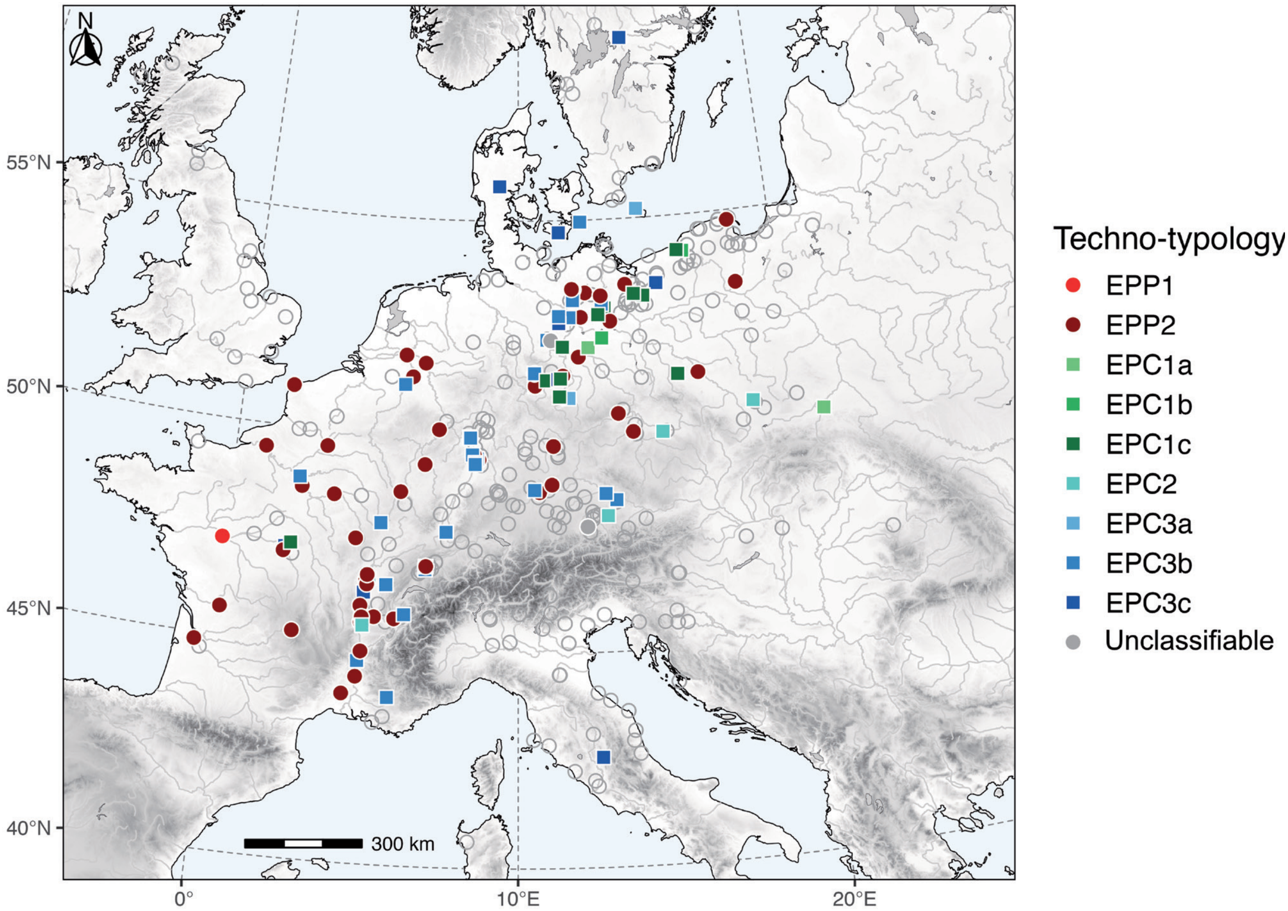

Fig. 9 – Distribution of Bz D to Ha B1 (ca. 1300-950 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

lier. The *Achtkantschwert-Prinzip* still exists: this *chaîne opératoire* is still used to make antennae swords of type Tarquinia, mostly found in the Italic Peninsula and around the Alps (Dumont, 2022, p. 296–301; Dumont, 2024). In parallel, less specialised, and more versatile techniques are used, especially the secondary casting (type EPP2). This technique is particularly used to produce swords found alongside the Saône and Rhône valleys, as well as in the southern Baltic region. Unlike the north-alpine tradition, characterized by a very specialised set of techniques only used in the framework of solid-hilted production, the important use of secondary casting cannot be interpreted as the result of a centralised production. This is indeed a widespread technique across Bronze Age Europe, used to produce artefacts, such as pins, but also to repair broken or flawed objects (Drescher, 1958). Instead, the development of this technique alongside several other *chaînes opératoires* can be linked to a nuclearization of the production centres. Swords are now produced is many smaller workshops by less specialised and more versatile craftspersons. The coexistence of different technological traditions in several regions, especially south of the Baltic Sea where there are also swords of types EPC1a-c sometimes made without rivets (Bugaj, 2005), shows that swords found in the same region were produced by different production groups.

The stylistic and technological homogeneity characterizing the monopoly phase disappeared at the very end of the Bronze Age. The monopoly phase showed a strong stylistic and technological homogeneity, with a stylistic tradition matching a *chaîne opératoire*. During the 9th century BC, this is no longer the case. We do not observe any correlation between production techniques and types of swords. For example, there are swords of the Mörigen type with a solid hilt produced by secondary casting (type EPP2) as well as with hollow hilts belonging to types EPC1b, EPC1c, EPC2, EPC3a, EPC3b and EPC3C (Dumont, 2022, pl. 142; 2024). During the disruption phase, the manufacture of solid-hilted swords does not seem to be restricted to a single production group. It rather seems to have opened up to many production units that includes craftspeople with different *habitus* and possibly for different socio-cultural backgrounds.

The typological diversification observed during Ha B2/3 as well as the evolution of the distribution pattern of solid-hilted swords, which are not found anymore in the Carpathian Basin but rather between the Saône-Rhône axis and the southern Baltic region (fig. 10), also indicates possible changes in the users. Could these variations be correlated with the development of new groups of sword bearers, different from the groups of the monopoly phase. The organisation of production is therefore different. The existence of reusable moulds made of bronze (Erlingshofen, Germany: Overbeck, 2018, p. 81–82) or stone (Lac du Bourget, France: Kerouanton, 2023, p. 164) shows that these swords may have been serially produced, possibly in relation with an unregulated production which is no longer limited to a limited group of users sponsoring the crafters.

CONCLUSION

The investigation of production techniques and the development of a technological classification framework have proved to be effective tools to fill the gap created by the lack of direct archaeological traces connected to metalworking activities. They offer a new barometer to explore the variations in the organisation of production of solid-hilted swords throughout Bronze Age Europe.

The manufacture of the earliest solid-hilted swords during Bz A2 and Bz B is not well documented as few of these swords have been X-rayed. Available data suggests an important technological diversity with the use of peculiar techniques that are not used any further in later periods. Together with the typological diversity and the small number of swords known in Europe, this seems to be an experimental phase. Several versatile production units were probably involved in their manufacture. Although the scale of the production cannot be determined precisely, the few swords found for that phase indicate they may have been prestige artefacts carefully crafted and dedicated to a very small portion of the population.

Changes occurred in the middle of the 15th century BC (Bz C) with the outbreak of octagonal-hilted swords. They were manufactured in a new way with a hollow hilt fixed to the blade by locking the tang inside the hilt and adding two rivets on the guard. As virtually all solid-hilted swords found between the Rhine valley and the Carpathian Basin until the 10th century BC (Ha B1) are manufactured in the exact same way, this phase corresponds to the centralisation of the production within a single production group. Considering the high degree of technological standardisation, they were probably made by a few highly-specialised craftspersons. These swords were also all unique and may have been made to order. They were probably not widely available and their access was probably restricted to a part of the population. This socio-cultural group may have sponsored the crafters involved in the manufacture of these swords, making it a form of attached production.

Things changed in a radical way at the very end of the Bronze Age during Ha B2/3 (ca 9th century BC) with the outbreak of multiple technological traditions and the use of less-specialised techniques such as over-casting, as well as reusable moulds enabling serial production. At that time, the production of solid-hilted swords probably opened up to a wider range of craftspeople, in line with an increase in demand. This nuclearization of the production centres at the end of the Bronze Age matched changes in the morphology, decoration and distribution of these swords. This period is thus characterised by important changes in the organisation of production, consumption and diffusion of solid-hilted swords, probably corresponding to the emergence of new groups of users and producers.

The underlying reasons of the major changes observed in the production and consumption of solid-hilted swords at the very end of the Bronze Age are not well understood. This would require more technological data to get a better understanding of the geographic variations in production techniques, especially in the north-alpine region and in the Italic peninsula, where few swords were investigated using X-ray imaging techniques. This would also require a wider study including other types of metalwork to determine the scale and extent of the changes observed through solid-hilted swords.

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