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The medieval bombards of Meaux: Manufacturing processes and supply of the metal

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ABSTRACT

Well-dated and preserved medieval bombards are rare and, most of the time, only exist in single exemplar. They are nevertheless exceptional testimonies of the medieval metallurgical skills. The musée de l'Armée (Paris), owns six impressive powder chambers, found in the same place (Meaux, France) and dated from the same period (15th c.). For the first time, this unique set has been studied by classical metallographic investigation, and recent approaches on slag inclusions using SEM-EDS and LA-ICP-MS analyses. The analyses permit to discuss the nature of the metal as well as the process used to obtain the metal (bloomery or finery) but also to consider the diversity of provenances for the metal that was used. These results suggest that five bombards may have been forged in the same area and possibly even in the same workshop, but anyway using metal produced through the bloomery process.

1. Introduction

The bombards are medieval large bore guns, that could weigh several tons (i.g. Mons Meg exposed in Edinburg Castle or Dulle Griet exposed in Gent) (de Crouy-Chanel, 2014). They were designed to throw stone round shots and appeared with the artillery development at the end of the 14th and the beginning of the 15th century for the cities attack or defence. They were produced either in iron alloys or bronze, however this study focuses only on iron forge-welded bombards. Bombards fabrication was a technical challenge in medieval times, both because of the large quantities of involved metal and the required performances of resistance. Therefore, several authors have highlighted the artisans know-how (Benoît, 1987; Gaier, 1973), in making these impressive pieces. Several studies (Balasubramaniam et al., 2004; Benoit et al., 1995; Smith and Brown, 1989; Walker and Hildred, 2009) have been carried out to decipher the way bombards were assembled. Results have showed that they were made of two distinct parts: the barrel and the powder chamber. The barrel was constituted by long staves running on its whole length and bound together with multiple hoops. Regarding the powder chamber, several hypotheses were formulated, from the use of cast iron to the direct forging of crude iron products. Other approaches, based on both experimental and calculated data, have also been carried out to estimate the effectiveness of these weapons according to their assemblage (Hansen, 2001; Lefebvre et al., 2004; Lefebvre and Gillet, 2000).

Beyond the assembling techniques of these imposing guns, the nature of the metal and the possible heat treatments applied by the craftsmen are also crucial to consider. Indeed, they determine the resistance of these objects subjected to violent shocks. Previous studies (Balasubramaniam et al., 2004; Benoit et al., 1995; Smith and Brown, 1989; Walker and Hildred, 2009) have revealed that the guns examined were made of low or medium-carbon steel (%C < 0.8) with significant heterogeneities in the metal (carbon amount, grain size, slag inclusions and phosphorus content). Widmanstätten structures were also frequently observed, suggesting a high-temperature forging and welding followed by a fast cooling. On the staves, Starley has noticed higher carbon structures, lower phosphorus content and finer grains than from the powder chambers and hoops (Smith and Brown, 1989). For the author, it could be explained by differences within the manufacturing process. Contrary to the staves, the powder chambers were shaped at high temperature, which would lead to a more important decarburization, at least on the surface. Equiaxed ferrite grains were observed most of the

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Table 1
Bombards dimensions.

Name	Total length(cm)	Internal diameter (cm)	External diameter (cm)	Weight estimation (kg)
N21	93	21	55	1440
N22	104	18	50	1413
N23	121	17	39	910
N24	122	22	45	1122
N26	100	19	37	709
N27	89	13	42	832

time on the powder chambers by Benoit et al., showing also evidence of hammering and holding the metal at high temperatures for a long time (Benoit et al., 1995). However, as the authors point out, the small number and size of the examined samples examined did not allow to draw definitive conclusions. Indeed, archaeological bombards are scarce. To the authors' knowledge, archaeometallurgical investigation have been carried out on only a dozen of forge-welded and they all are single finds.

Another interesting aspect relies on the nature of the ironmaking process used to produce the bombards. At the end of the Middle Ages important changes occurred in the iron and ferrous alloy production chain. The new indirect process, made up of blast furnace and finery, appears in the north of Europe between the 12th and 15th centuries (Awty, 2007; Belhoste, 2001; Dillmann and L'Héritier, 2017, 2007). The *chaîne opératoire* related to this process differs from the bloomery one as two main steps are involved. In the first one cast iron is produced, which gives the possibility to create objects by moulding. This step is followed by a refining of the cast in order to produce iron or steel alloys. If most of a bombard should be made of this latter, some parts of the bombard, like the powder chamber, could have been made from cast iron. The archaeological bombard of Nancy (France) was, for instance, made entirely with this material (Benoit et al., 1995). Some texts dating from the 15th century also mention small pieces made of cast iron (Belhoste, 2008). Thus, several authors have assumed that the large parts of bombards, such as powder chambers, were made of cast iron and moulded parts (Belhoste et al., 1991). However, the archaeological bombard of Nancy is the only reported example of the use of cast iron to make bombards. Eventually deciphering bombards metal (and its manufacturing process) is therefore part of an extensive approach to study the use and diffusion of the indirect process and its impact on medieval technical and economic systems. Determining the ironmaking process of ferrous alloys is possible by studying the chemical composition of entrapped slag inclusions ("SI") (Dillmann and L'Héritier, 2007; Disser et al., 2014). Furthermore, the chemical analyses of the SI also give the opportunity to determine the origin of the metal produced by the bloomery process, as they carry the chemical signature of the metallurgical production area. Then, by determining this signature with both major and trace elements (Blakelock et al., 2009; Buchwald and Wivel, 1998; Charlton, 2015; Coustures et al., 2003; Desaulty et al., 2009; Dillmann et al., 2017; Disser et al., 2016; L'Héritier et al., 2016; Leroy et al., 2011, Leroy et al., 2017, Leroy et al., 2012), and comparing them with geochemical database references, it is possible to test hypotheses on the origin of the employed materials. While large quantities of metal were obviously needed to make medieval bombards, the origin of the metal remains unknown. In addition to providing valuable information on the medieval European iron market, studying the provenance of the bombards materials could also give some insights into the location of the workshops. Excepting Mons Meg, for which historical sources identified its manufacturer, Jehan Cambier (Smith and Brown, 1989), little is known about the location or the organization of the gunsmiths workshops.

Therefore, the present paper aims to a better knowledge of the bombards metallurgy by examining with all the aforementioned approaches the exceptional set of 6 well-dated (15th c.) bombards related to a single archaeological context (Meaux, France).

Fig. 1. "A" Photograph of bombard N24, "B" photograph of bombard N27

Table 2
Samples localisations.

Bombard	N° Sample	Localisation
N23	N23A	Hoop (Powder chamber and barrel joint)
	N23B	Hoop or stave
	N23C	Hoop or stave
	N23D	Rear end of the powder chamber
N24	N24A	Hoop (Powder chamber and barrel joint)
	N24B	Hoop (Powder chamber and barrel joint)
	N24C	Rear end of the powder chamber
	N24D	Internal hoop of the powder chamber
N21	N21 A	Stave?
	N21 B	External hoop
	N21 C	Rear end of the powder chamber
N22	N22 A	Stave?
	N22 B	External hoop
	N22 C	Rear end of the powder chamber
N26	N26 A	Stave?
	N26 B	External hoop
	N26 C	Rear end of the powder chamber
	N26 D	Internal hoop
N27	N27 A	Externa hoop
	N27 B	External hoop
	N27 C	Rear end of the powder chamber

2. Set of artefacts

The bombards of Meaux seem to be the last evidences of the cannons used by the English and left on site after the siege of Meaux in 1422. They were dismantled in the 18th century. Only the powder chambers (N21, N22, N23, N24, N26 and N27) remained. The barrels, probably easier to dismantle are likely to have been recycled in 1726 (Carro, 1865; Leduc, 2008). These were used as bollards in Meaux city until 1843, when they became part of the collection of the Artillery Museum (Leduc, 2008). Their weights have been estimated around 1000 kg (see Table 1 and reached 1440 for the bombard N21. The bombard N27 is the smaller one, with a powder chamber diameter around 13 cm (see Fig. 1. They are made of several layers of staves and hoops, but their advanced state of corrosion makes their original assemblage shaping difficult to identify. Detailed descriptions of the pieces are available in the publication "Nouveaux regards sur l'artillerie primitive XIVe s.- XVe s." (Collectif, 2008).

Samples of several tens of mm^3 were collected at different locations on the bombards (Table 2. Due to the advanced degree of corrosion in some places, the position of the sample (powder chamber, hoop, stave) could sometimes not be clearly identified.

3. Materials and methods

All analysed samples were mounted in epoxy resin, then grinded using SiC abrasive paper (grade 80 to 1200). Final polishing was performed using Struers diamond polishing medium 3 and 1 μm. Metallographic etchings were done on the samples using 3% Nital. Then, optical observations were performed using an OLYMPUS microscope (model BX51) in order to estimate carbon content, distinguish the different kinds of inclusions and possible welding lines. An average carbon content and a weighted standard deviation were estimated for each sample and plotted into a graph of bell-shape, following the methodology of

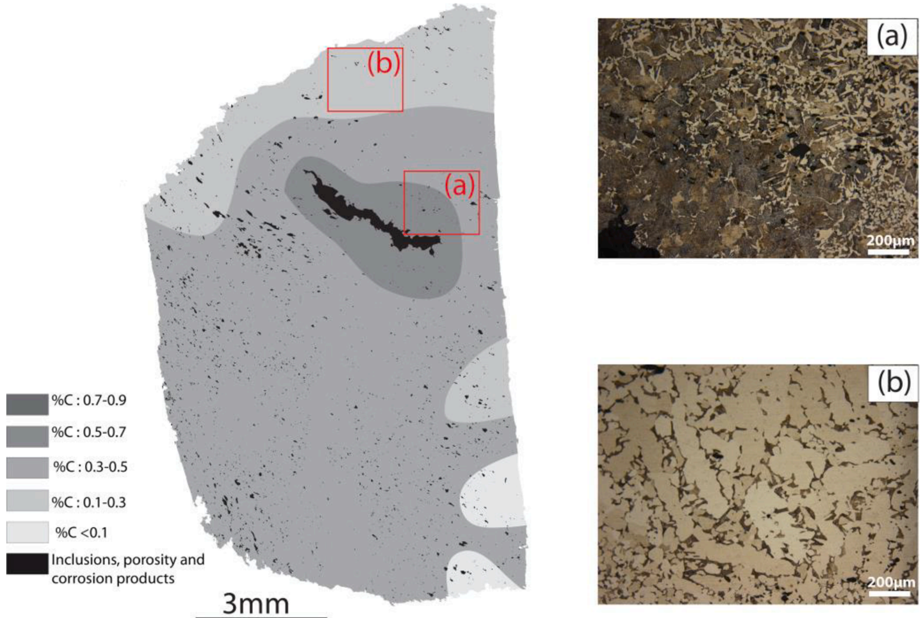

Fig. 2. Metallographic study for sample N24C showing the distribution of the carbon content, inclusions, and pores.

Pages et al., and Leroy et al., (Leroy et al., 2017; Pagès et al., 2011).

Major elements were quantified using Energy Dispersive Spectrometry (EDS) coupled to Scanning Electron Microscope (SEM) with a 15 kV accelerating voltage. Each spectrum corresponding to a single inclusion is treated following the ZAF semi quantification method using IDFix and Maxview softwares (SAMX company). The weight content of detected elements is then calculated and normalized to 100%. Results are expressed as oxides. For minor elements (between 0.5 and 1 wt%) it was assumed that the relative quantification error is about 10%. For the other elements (>1 wt%) the error is over-evaluated by assuming a relative error of 2%. A minimum of 30 inclusions were analysed for each sample. Full details on the procedure can be find on Disser et al., (Disser et al., 2014).

The discrimination between the two smelting processes was done by following the procedure proposed by Dillmann and L'Héritier (Dillmann and L'Héritier, 2007) and Disser et al. (Disser et al., 2014). It implies to identify SI families with constant Non Reduced Compounds (NRC) ratios ($\%Al_2O_3/\%SiO_2$, $\%K_2O/\%CaO$, $\%MgO/\%Al_2O_3$). Then, a weighted content of each considered element called ($\%E_i^*$, see Eq.1) and a sub-compositional ratio ($\%E_i^{**}$, see Eq.2) were calculated according to the following formula:

$$\%\boldsymbol{E}_i^* = \sum_{i=1}^{n}(\%\boldsymbol{E}_i \times \frac{\boldsymbol{Si}}{\boldsymbol{St}}) \tag{1}$$

$$\%\boldsymbol{E}_i^{**} = \frac{\%\boldsymbol{E}_i^* \times 100}{100 - \%\boldsymbol{E}_{FeO}^*} \tag{2}$$

$\%E_i^*$: average weighted content for all the inclusions of an artefact coming from the smelting stage

$\%E_i$: composition of a given inclusion

Si : surface of the inclusion analysed

St : sum of all the inclusion surfaces

Finally, the determination of smelting process was made by comparing the amount of NRC compounds ($\%E^{**}$) with a reference database. The comparison has been made by using both the abacus proposed by Dillmann and L'Héritier (Dillmann and L'Héritier, 2007) and the logistic regression to model the data, both useful for solving unspecified cases. Then, a probability that the sample is associated with the finery process is calculated according to the model (Disser et al., 2014). However, as pointed out by the authors, an area, for which the process cannot be identified, remains, due to an overlap of the chemical features of the two processes in the reference dataset (it was already observed with the abacus proposed by Dillmann and L'Héritier built with the same dataset). To avoid the risk of making wrong predictions Disser et al., recommended for the logistic regression approach to define the reduction process as "undetermined" according to the following threshold: $0.3 < p_{finery} < 0.7$. Therefore, the process will be considered as "bloomery" when $p_{finery} < 0.3$ and indirect when $p_{finery} > 0.7$.

Only the metal made by the bloomery process can lead to a provenance analysis, as the chemical signature of the iron ore is lost from the very first step (through cast iron production) of the finery process. Trace elements were quantified using Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at the Ernest Babelon Centre (UMR-5060 IRAMAT CNRS, Orléans, France) on a dozen of SI per sample. The laser repetition rate was set to 7 Hz, the ablation time to 50 s, and the ablation crater between 50 and 80 µm in diameter depending of the SI size analysed. The quantification procedure fixed by Gratuze et al. was used (Gratuze et al., 2001) using both internal standardization and external calibration. As the amount of removed material is not the same for each ablation, the signal obtained for each trace element was compared to the internal standard: the isotope ^{28}Si. Then, silicon values determined previously by SEM-EDS on SI were used to recalculate trace element concentrations instead of normalizing all contents to 100%. The calculation process also implies using an external standard, the certified glass NIST610. With this method, a significant number of trace element (up to 39) were quantified in the SI.

Among the measured trace elements, only a restricted set could be quantified with an acceptable accuracy of measurement at the concentrations observed in the samples: Y, Nb, La, Ce, Pr, Nd, Sm, Eu, Yb, Hf, Th, U. This set of elements was selected to compare the chemical signatures between the samples through multivariate analyses. To ensure scale-invariant representations, a log-ratio data transformation (see Eq.3) was applied for the selected traces elements as recommended by several authors (Aitchison, 1982; Disser et al., 2016; Leroy et al., 2012).

$$\mathbf{X_{ij\_E}} = \mathbf{Log}([\mathbf{E}]) - \frac{1}{\mathbf{N}}\sum_{\mathbf{k}=1}^{\mathbf{N}}\mathbf{Log}([\mathbf{E_k}]) \tag{3}$$

Where:

X_{ij_E} is the transformed value for each element

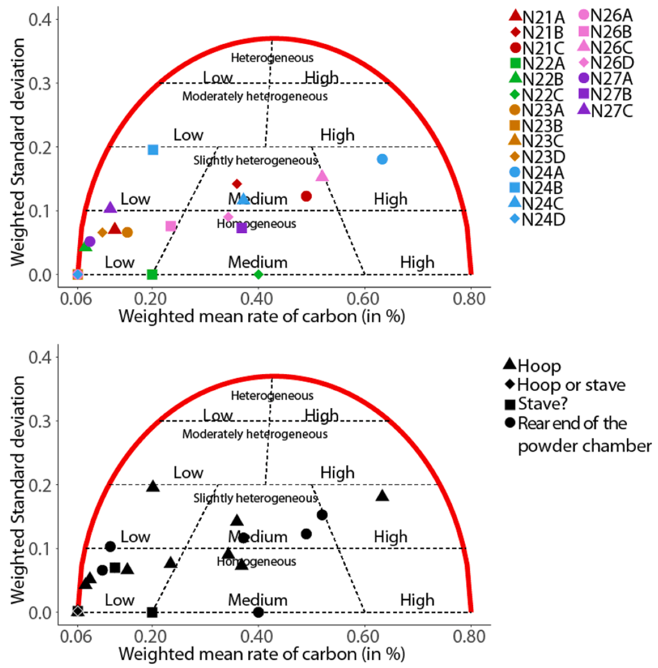

Fig. 3. Compositional domains of the bombards alloy structure according to the bell shape diagram proposed by (Leroy et al., 2017).

[*E*] is the measured element concentration

We have chosen to lead a non-supervised multivariate statistical approach, PCA (Principal Component Analysis) as its implementation in ancient iron provenance investigation has already provided good results on highlighting provenance groups (Charlton et al., 2012; Dillmann et al., 2017; Disser et al., 2016).

4. Results and discussion

4.1. Nature of the metal

All the samples are constituted of heterogeneous ferritic or/and hypoeutectoid steels. An important heterogeneity of the distribution of the carbon content was noticed, within each sample (see Fig. 2. In addition, weighted mean rate of carbon contents is variable even for samples coming from the same bombard (see for instance samples N24 A and D in Fig. 3. Most of the samples show relatively low weighted mean rate of carbon contents (<0.2) but some more carburized samples are also observed in medium carbon steel (N21B, N21C, N22C, N24C, N26C, N26D, N27B), and high carbon steel areas (N24A). Four of them (N21C, N22C, N24C, N26C) were taken from the rear of the powder chamber of the bombards. Nevertheless, two samples also taken from the powder chamber (N27C, N23D) were made of low carburized iron. No ghost structure indicating a significant amount of phosphorus in the metal was observed.

Furthermore, no evidence of casting was visible. Hence, this does not help to prove that the production of cast iron have had a major influence on the fabrication of the bombard. Although the use of cast iron seems the easiest way to produce imposing artefacts such as bombards, this result could be explained by the mechanical behaviour of the cast, more brittle compared to steel (Benoit et al., 1995). While the mechanical behaviour of cast iron may have impeded its use for late medieval artillery, the technical limitations due to the casting of pieces as large as barrels or powder chambers may also have played a role in this choice. The pieces have to be cast in one go and in a very short time to avoid structural weaknesses. This implies the availability of a large quantity of cast iron either in the blast furnace crucible or in a casting crucible. As the amount needed would have ranged from 0.71 to 1.44 tons, meeting

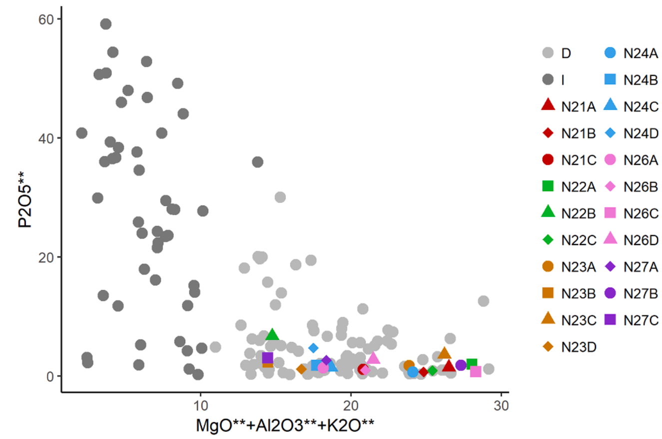

Fig. 4. Abacus.

Table 3
Results of the process prediction for the samples.

	Process	p_{finery}
N21A	bloomery	<0,01
N21B	Bloomery	<0,01
N21C	Bloomery	<0,01
N22A	Bloomery	<0,01
N22B	Bloomery	0,04
N22C	Bloomery	<0,01
N23A	Bloomery	<0,01
N23B	Bloomery	<0,01
N23C	Bloomery	<0,01
N23D	Bloomery	<0,01
N24A	Bloomery	<0,01
N24B	Bloomery	<0,01
N24C	Bloomery	<0,01
N24D	Bloomery	<0,01
N26A	Bloomery	<0,01
N26B	Bloomery	<0,01
N26C	Bloomery	<0,01
N26D	Bloomery	<0,01
N27A	Bloomery	<0,01
N27B	Bloomery	<0,01
N27C	Bloomery	0,07

such requirements may have been proved challenging for late medieval gunsmiths and may only have been used for pieces of smaller size than the Meaux bombards, as the bombard of Nancy (Benoit et al., 1995).

The analyses also suggest that steel alloys were not specifically selected. In addition, the amount of carburization does not seem to be related to a given part of the bombard (stave, hoops, power chamber…) in order to improve its resistance during shooting. Our results does not confirm the observations made by Starley, namely higher carbon structures on the staves compared to the powder chamber, that would suggest a deliberate choice of metal or a different manufacturing process, the powder chamber being built up at higher temperature which could have led to a decarburisation(Smith and Brown, 1989). No evidence of heat-chemical treatment as quenching or carburizing, part of the armour fabrication (Bérard, 2019; Williams, 2003) for instance at the same period, were found either. Eventually, the manufacture of the bombards is based on an unspecific and mostly heterogeneous metal as already highlighted by previous studies (Benoit et al., 1995; Smith and Brown, 1989). This feature could be compared to the pattern of metallic structures found in the metal used for cathedral and monuments during the Middle-Age, showing no specific material choice or heat treatments (Dillmann et al., 2003; L'Héritier et al., 2013; L'Héritier and Dillmann, 2010; Timbert, 2009). Most of the time, these reinforcements are also constituted of bars with sections and dimensions roughly comparable to the ones used for the staves. These products directly reflect the

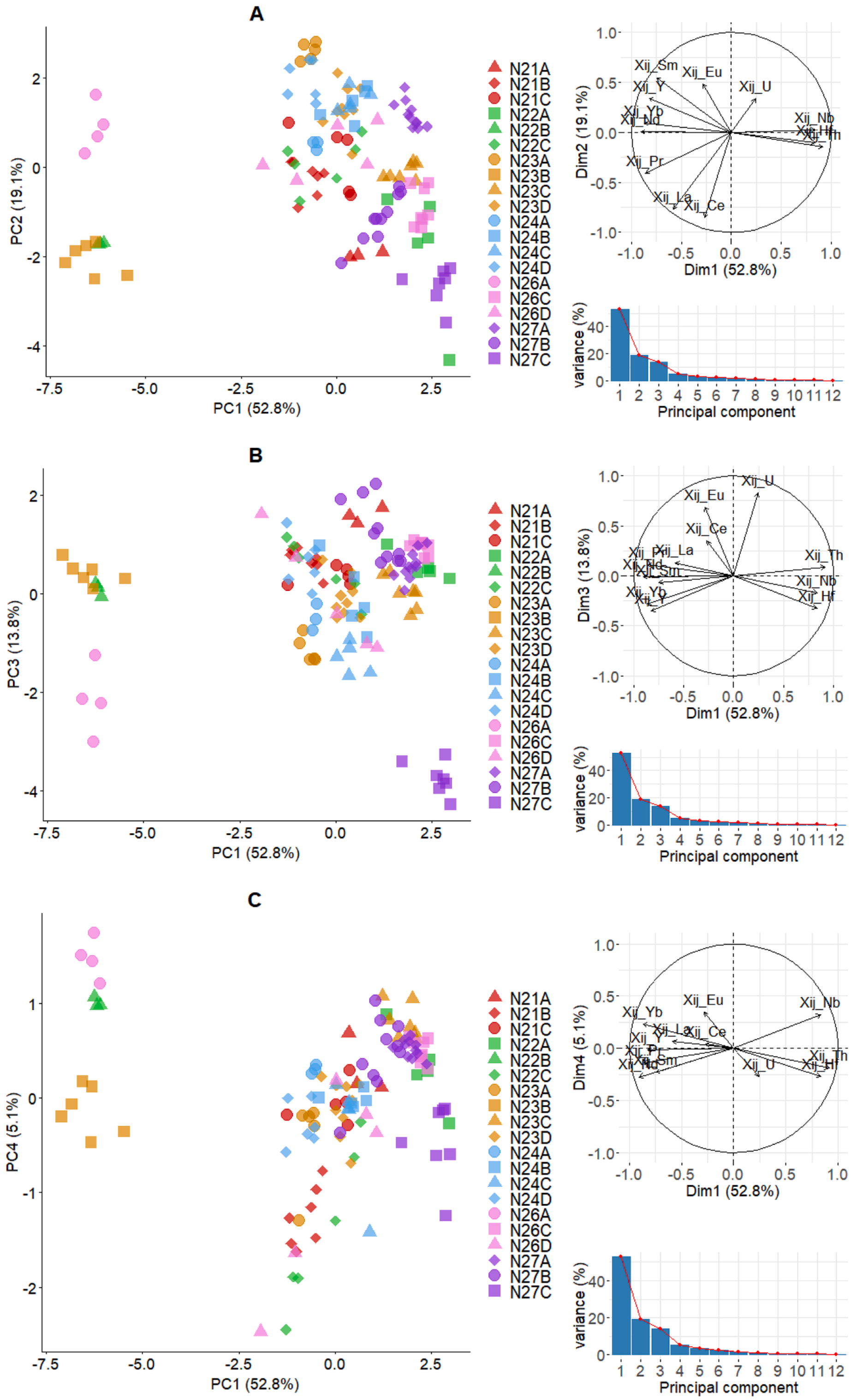

Fig. 5. "A": PCA carried out on transformed compositional data of SI projected onto PC1-PC2, "B": PCA carried out on transformed compositional data of SI projected onto PC1-PC3, "C": PCA carried out on transformed compositional data of SI projected onto PC1-PC4.

heterogeneity of the bloom originating from the furnace of reduction or refining, where the thermodynamic kinetic conditions are heterogeneous. At least, the metal used for the manufacture of bombards looks quite common, telling us that the technical prowess would lie rather in the techniques of shaping and assembly at the forge.

4.2. Smelting process

All the samples are located in the bloomery process area on the abacus (see Fig. 4 and have a high probability to have been made by the bloomery process ($\boldsymbol{p}_{finery} < 0.08$) according to the logistic regression (see Table 3.

In the 15th century, the indirect process is attested in several areas in Europe, in Sweden (Magnusson, 1985), the North of Germany and West

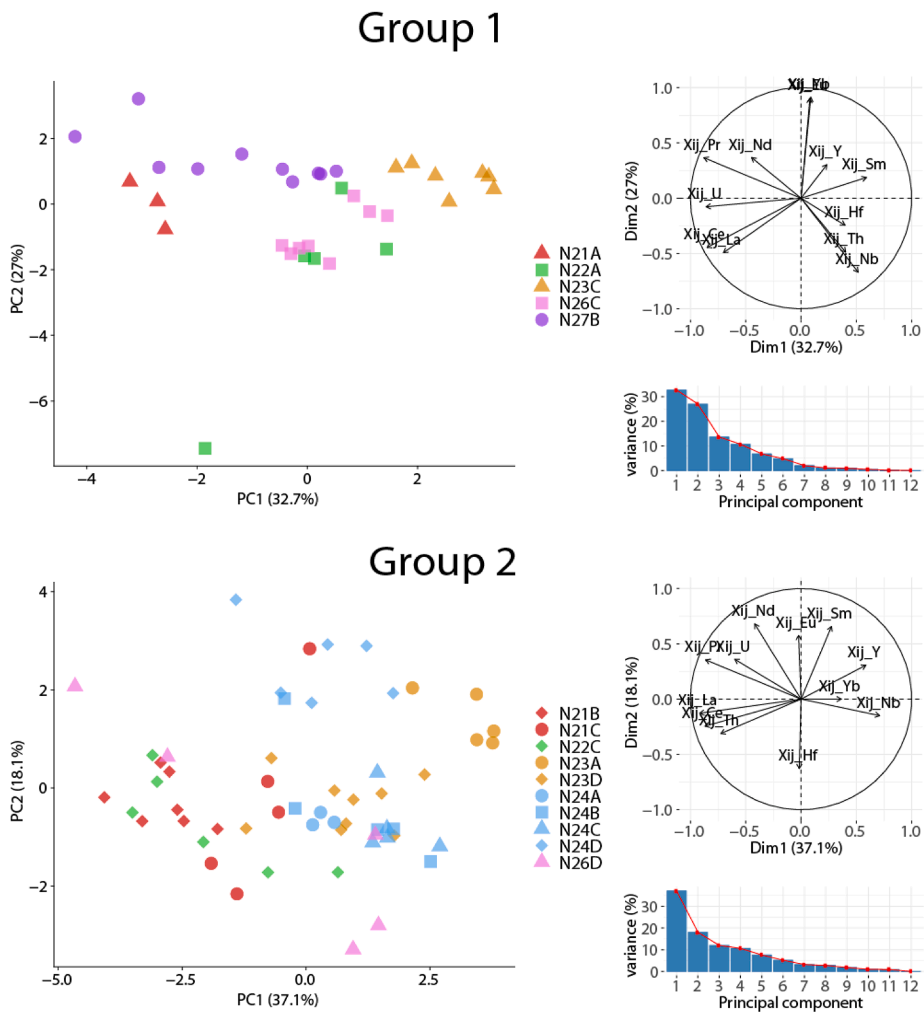

Fig. 6. PCA carried out on the transformed data of SI projected onto PC1 and PC2 for Group1 and Group2.

of Switzerland (Tauber and Senn, 2020) since the 13th-14th c. (Jockenhövel, 2013), in Namur since the second half of the 14th c. (Awty, 2007), in the kingdom of France since the 14th c. (Rouillard, 2003), in Champagne (Verna, 1995) and in Normandy (Belhoste et al., 1991). Notably, the first evidences in England are dated from the 16th century (Cleere and Crossley, 1995).

It is important to notify that the development of the indirect process in a region does not necessarily imply the disappearance of the direct process at the same time. Both historic, archaeometric and archaeological data have demonstrated that the two processes have coexisted during several decades or centuries in numerous areas (Dillmann and L'Héritier, 2017). Consequently, the process used to obtain the metal is not a reliable marker to identify the provenance of the metal or the location of a workshop. Thus, should the bombards of Meaux be made in England, we can only confirm that our results are compatible with the historical data regarding the diffusion of the indirect process in the North of Europe. However, this hypothesis is not asserted, as in the military framework this kind of artefact was often employed successively by several groups, above all during war background (Collectif, 2008).

4.3. Metal provenance

PCA results are presented in Fig. 5. Only the four first components which express 90% of the variance are presented. All the SI belonging to the same bombard are plotted in the same colour..

On Fig. 5 C three samples are isolated: N22B, N23B, N26A while Fig. 5 A isolates sample N27A. Lastly, on Fig. 5 B three groups can be defined:

- Group 1: N21A, N27B, N22A, N26C, N23C
- Group 2: N24A, N24B, N24C, N24D, N21C, N21B, N23A, N23D, N26D, N22C
- Group 3: N27C.

Then, in order to determine possible subsets within these clusters, new PCA were performed on each group. Only the projections on the plans defined by the principal components which contain pertinent information to differentiate groups are presented (PC1-PC2) (Fig. 6). It was checked that the remaining components do not contain relevant information to distinguish provenance groups (see Supplementary Materials).

Samples N22A and N26C belonging to Group 1 stay mixed contrary to samples N21A, N27B and N23C, whereas for Group 2 sample N23A have a different chemical signature from the others, forming one cluster. A summary of all the results is presented on Fig. 7.

A first observation is that, except for N24, all the bombards were made with metal of several origins. It strongly suggests that, faced with the large quantity of metal required to manufacture these objects, gunsmiths probably had to call on different suppliers. This hypothesis is supported by historical sources such as a purchase dated from 1375 to make a cannon in which three different metal supplies are mentioned (de Crouy-Chanel, 2014).

Furthermore on Fig. 7 only bombard N27, which differs most from

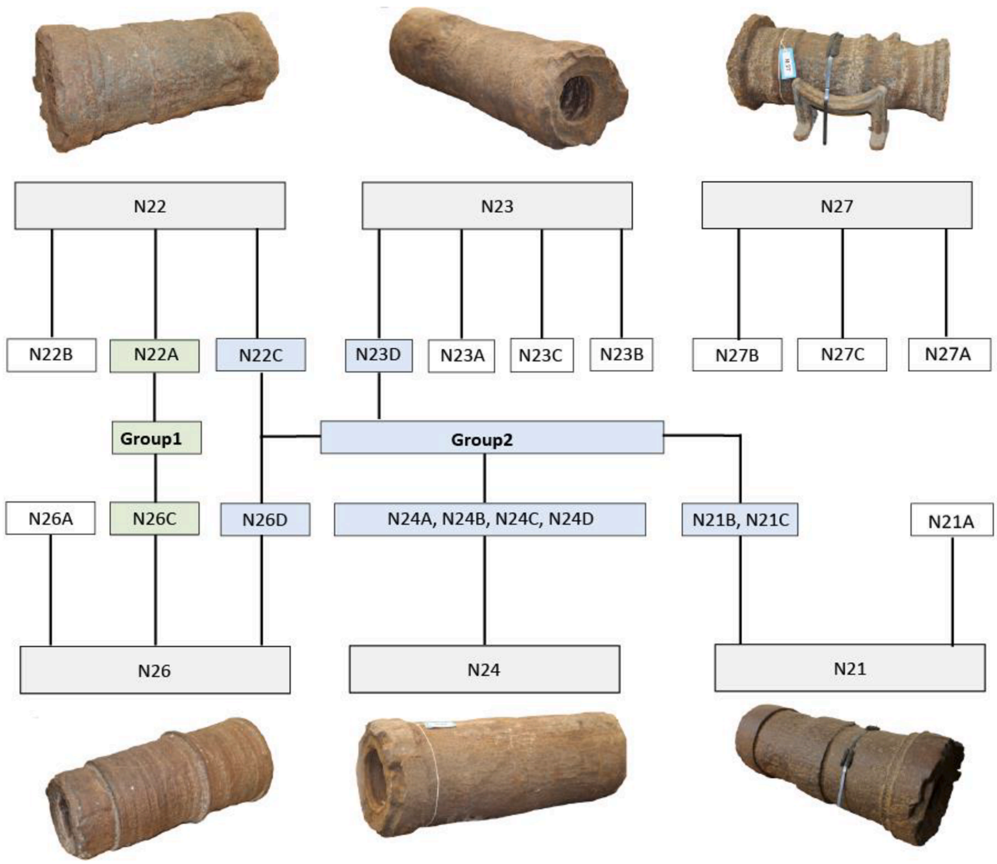

Fig. 7. Origin of the metal: summary of the results for each bombard.

the others by its size and shape, is isolated from a chemical point of view. All the other bombards appear to have been made at least with one common supply of metal (Group gathering N24A, N24B, N24C, N24D, N21C, N21B, N23D, N26D, N22C). Further research is needed to determine to which geographical area it may correspond. However, this result could suggest that all the powder chambers were made at the same time, in the same geographical area or even by the same workshop, which used several metal supplies to produce them. The latter implies that the work was performed by an important workshop, able to set up equipment and people to forge at least five massive powder chambers.

5. Conclusion

This study presents archaeometric results on an unique assemblage of six bombard parts found at the same place (Meaux, France) and dated from the same period (15th c.). Our results confirm previous observations made on other pieces dated from this period: no deliberate choice was made regarding the nature of the ferrous alloys. Metal used to produce bombards was an ordinary material, showing heterogeneities in carbon content along with no heat-chemical treatment. The specific use of steel material, more resistant than other ferrous alloys, has not been evidenced on any of the studied parts of the bombards. Our results, based on a limited number of pieces, do not allow us to affirm that cast iron, whose use by moulding was attested in Northern Europe at this period, played a major role in the manufacture of these objects. Nevertheless, the assembly of these impressive artefacts certainly required a technical craftsmanship. For the first time, major and trace elements of SI embedded in the metal were measured. The results showed that bombards of Meaux were made by using a metal produced through the bloomery process. This observation is compatible with the actual data known for the diffusion of the indirect process in Europe confirming the concomitance of the two processes at this period. The analysis of trace element in the SI revealed a supply heterogeneity for each bombard, except for bombard N24. This result could be explained by the need of important quantities of metal to make these massive pieces. Nevertheless, except for bombard N27, metal from a same origin can be found in each of the bombard, which may suggest a synchronous manufacturing of the bombards, at the same place or even by the same workshop. This key observation, reinforced by the morphological similarities of the bombards, brings new insights to the fabrication of these massive pieces that were supposed to be realized in an isolated way.

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Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2021.103307.

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