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RESEARCH

New remarks on the mid-17th-century gunfounding in Northern Europe: archaeometric analysis of scrap bronze ordnance recovered from a Dutch merchant vessel lost off Cadiz, Spain

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Abstract

This article deals with the study of an assemblage of scrap bronze guns recovered from the Delta III site, identified as a Dutch merchant ship lost in the port of Cadiz, Spain, about the third quarter of the seventeenth century. This kind of remains is seldom preserved and therefore stands as a unique source for addressing modern bronze gunfounding. Its main characteristics and drawbacks were outlined and discussed on historical and archaeological grounds. The gun remains and casting by-products were recorded, and pieces were identified through their design, decoration, and marks. A metallurgical study of selected samples was carried out by visual inspection and microstructural and chemical analyses by light microscopy and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy. A better understanding of the quality and manufacturing process of the pieces and the conditioning factors of the failed casting was achieved by this approach. Results provided new insights into the gunfounding process, with emphasis on a renowned atelier of German bell and cannon founders, along with the associated international markets and recycling practices.

Keywords Bronze guns · Mid-seventeenth century · German gunfounding · Dutch shipwreck · Archaeometallurgy

Introduction

Bronze guns, foundry technology, and ships

The production of bronze guns through the seventeenth century was a remarkable and highly-demanded metallurgical activity. Culverins, cannons, perriers, and mortars, comprised the main smooth-bore muzzle-loading pieces which were used both for field and naval service, often interchangeably.[1] They were thoroughly used in vessels of most European maritime powers (England, France, Netherlands, and Spain) until the mid of this century when the increased demand for warships led to a period of transition to the pre-eminence of the less expensive cast iron naval ordnance (Alcalá-Zamora y Queipo de Llano 1970–1971:244; Kennard 1986:161; Lavery 1987:85–87; Boudriot and Berti 1992:26).

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[1] For instance, British guns and other related supplies were in charge of the Board of Ordnance, which provisioned both the Army and the Navy. The same guns could often be used in either context and were usually cast in the same foundries (Lavery 1987:80).

Compared with cast iron pieces, bronze guns had several advantages: they show a better performance during firing; were less susceptible to burst (and if they explode, did not produce a deadly deflagration); were strongest and thinner, and therefore lighter; and their lifetime at sea was longer (Guilmartin 2005:28; López-Martín 2011:279; Ciarlo 2017:12–13). Unlike cast iron guns, a major drawback was their propensity to soften and sag or suffer another bore failure under continuous firing. However, this problem was hardly noticeable at that time. Bronze pieces were also easier to obtain: casting, rectifying, and decorating. Although gunfounders usually had to face manufacturing defects and failed castings, bronze could be readily re-cast without losing its desirable properties to obtain new sound pieces. As a recycling practice, melting down of bronze artefacts to cast operative guns was not unusual during the modern period.

The development of bronze naval ordnance, covering social, economic, political, and technical issues related to this process has been widely addressed (e.g. Lavery 1987; McConnell 1989; Boudriot and Berti 1992; Meide 2002; Hoskins 2003; Guilmartin 2005; Beltrame Ridella 2011; Ciarlo 2017; Brinck 2020a; Pascoe 2021; and references therein). Bronze guns are widespread across Europe and overseas, and numerous seventeenth-century pieces were located in wreck sites (and other underwater archaeological contexts) and subjected to detailed studies (e.g. Bravo Pérez and Bravo Soto 1990; L'Hour et al. 1990; Keith et al. 1997; Bound et al. 1998; Cates and Chamberlain 1998; Christoffersen 1998; Guilmartin 2005; van Duivenvoorde 2010; Brinck and Ridella 2016; Mihajlović et al. 2018; Brinck 2008, 2020a, 2020b; Oliver Laso and Ramírez Pernía 2021; Pascoe 2021).[2] Information has contributed to the assessment of wreck sites and a better understanding of the foundry technology.

The studies developed on ordnance associated with shipwrecks, fortifications, and other on-land sites, along with collections from museums, mostly deal with complete and often well-preserved guns, from a macroscopic and morpho-functional standpoint. Guidelines to gather information from pieces on a systematic ground have helped scholars in this venue (e.g. Roth 1989). The characterisation of the chemical composition of bronze guns is also a well-developed research theme (e.g. Riederer 1977; Forshell 1992:125–144; Samuels 1992; Northover 2011; Ashkenazi et al. 2017).[3] However, studies on the casting process and associated defects based on a microstructural analysis of archaeological remains are comparatively less frequent (e.g. Gilmour and Northover 2003; Żabiński et al. 2021; Iddan et al. 2022).

The ships' cargo and other elements in stowage, from unused goods to unserviceable or discarded objects, can provide valuable data on commercial and technological issues. Nonetheless, no previous work has been developed on failed casting products transported on board ships as scrap. In this regard, through the study of fragmented bronze guns recovered from the Delta III site, this article provides novel information to better understand the challenges of seventeenth-century bronze gunfounding.

A case of study: the cargo of the Delta III site

The Delta III site was located in 2014 in the port of Cadiz, Spain (WGS84: 36° 32′ 38.46″ N, 6° 16′ 3.26″ W).[4] The remains were recorded at a depth of 12 to 15 m, during an archaeological impact assessment developed for the construction of the new container terminal, under the direction of JM Higueras-Milena Castellano. The initial assessment conducted by M Gallardo Abárzuza comprised test pits surveys and a basic record of the remains. Thereafter, in 2016 a complete excavation of the ship's hull structure and its associated material culture was coordinated by R González Gallero. At this time, seven cast-iron guns identified as of Swedish origin, an anchor, and a bronze swivel gun (falconet) were temporarily retrieved and recorded (González Gallero 2016). In 2020, E Toboso Suárez led the record and relocation of the structural wooden remains to an underwater depot for guaranteeing their preservation.

The architectural traits of the lower hull stand for a plank-first shipbuilding system, a traditional method carried out at the northern Netherlands dockyards. Moreover, the dendrological studies of the structural remains suggest the ship was built using timbers from the west of Germany during the second half of the seventeenth century (González Gallero and Toboso Suárez 2021). This data and the provenance of associated material culture remains such as clay pipes and crucibles (Reig Gómez 2019; González Gallero 2023), among others, allowed suggesting this wreck site corresponds to a mid-to-late

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[2] The transport of bronze guns in stowage was not unusual, as pieces located at the hold of late-sixteenth and seventeenth-century shipwrecks attest to (e.g. Keith et al. 1997; Ridella et al. 2016). Old ordnance was also carried on board as cargo, to be sold or gifted. For instance, six culverin-type guns from the 60-gun galleon *Santissimo Sacramento* (1668) were dated from the mid-to-late sixteenth century (Brown 2005).

[3] The archaeometric studies of iron guns and ammunition have also provided unique data for the understanding of materials and casting technology (e.g. Crossley 1975; Bethencourt et al. 2013; Ciarlo and Argüeso 2019).

[4] The location refers to the archaeological site. Coordinates were taken with a standard GPS by one of the authors (RGG).

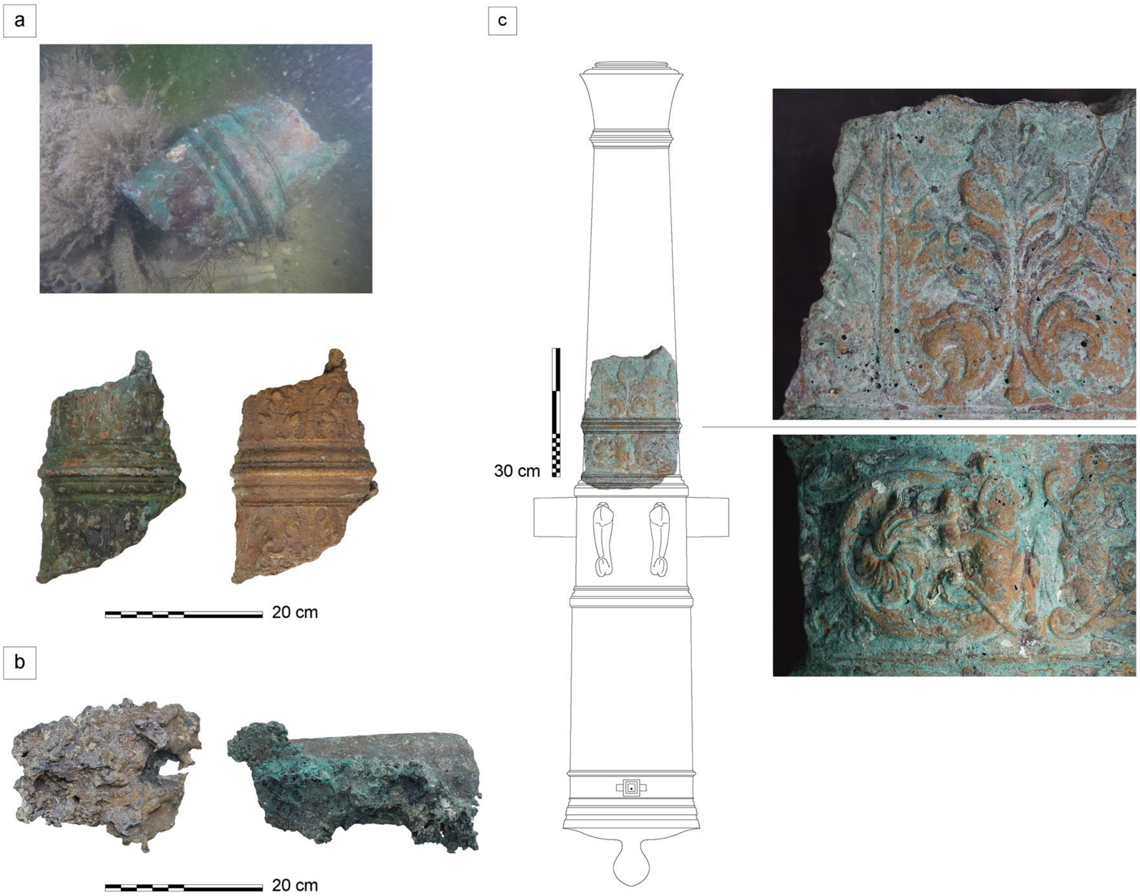

Fig. 1 Bronze cannon remains recovered from the Delta III site: **a** in situ; in the lab, just after its retrieval from the site; and after stabilisation (No. DIII-822); **b** amorphous bronze lump (No. D3-20–6) and part of a barrel welded to a casting by-product (No. D3-20–9); and **c** chase fragment of piece No. D3-20–11, with a decoration combining acanthus leaves and figurative motifs. The drawing is a simplified version of a gun cast by German founder Albert Benningk in Lübeck (1669), now located at the Army History Museum (Heeresgeschichtliches Museum), in Vienna, and illustrated by Boeheim (1884:32–33; see also Peterson 2014a:977–978). Images: R González Gallero and CAS-IAPH archive (**a**); and NC Ciarlo (**b**, **c**)

seventeenth-century Dutch merchantman (see González Gallero 2016, for a primary assessment of the entire collection).

More than a hundred fragmented bronze guns and casting by-products (lumps) were located at the ship's hold, mainly at the stern area, and in the surroundings of the hull's structure. They were recorded and partially retrieved in 2016 and moved to the lab of the Centre for Underwater Archaeology of Andalusia belonging to the Andalusian Institute of Historical Heritage (CAS-IAPH) for their preservation and study (Fig. 1). Moreover, in 2020, an array of similar remains scattered in the area—not directly associated with the wooden remains—was also retrieved to the surface. Environmental conditions prevailing in the navigation channel where the wreck site is located may have occasioned a dispersion of the remains, especially those of small dimensions. Therefore, the recovered bronze objects from the excavation area likely constitute only a portion of the original cargo.

During the stabilization process carried out in 2016–2019 at the CAS-IAPH, several samples were selected for analysis aiming to assess the alloy's quality and manufacturing process of these defective pieces. Additional samples were obtained from the remains recovered in 2020 after they were stabilised. The entire collection will be finally moved to the Archaeological Museum of Cadiz. The characterisation studies were developed at the Laboratory of Studies and Conservation of Culture Heritage (LEC-PH) of the University of Cadiz, under one of the author's (MBN) supervision.

The studied materials represent but a sample of the vessel's cargo. From archaeological interventions, a total of 40 bronze gun parts and 120 casting by-products were retrieved and catalogued. The size of most fragments ranges from ca. 20 to 40 cm in length and corresponds to gun barrel pieces, yet bigger pieces were also recovered. The bronze lump remains are amorphous. In total, they weigh 1443 kg and 22 kg, respectively. As guns' parts

Table 1 A brief description of guns and other bronze casting remains sampled for characterisation studies. *This sample was originally catalogued as NTC/12/DR/270

Object ID	Category	General description	Weight (kg)	Additional information
DIII-835	Gun and lump	Two small parts of a gun barrel fused by an amorphous casting by-product	44	
DIII-847	Gun	First and second reinforces. It is broken ahead of the chase astragal and fillets	509	The cascable, dolphins and left cascable are broken/miscast. The breech ogee and chase have decorative motifs. The barrel exhibits the coat of arms of Hamburg
DIII-S/D*	Gun and lump	Part of the chase (broken) and muzzle, with a casting mass welded to its surface	69	The mouth, face of the muzzle, and muzzle astragal and fillets are preserved with a certain degree of detail
D3-20–01	Gun	The fore part of the muzzle	32.5	
D3-20–02	Gun	Barrel fragment	43	Corresponds to a section of the first (most likely) or second reinforce-ring and ogee
D3-20–03	Gun	Barrel fragment	17	
D3-20–04	Gun	Barrel fragment	14.5	
D3-20–06	Lump	Amorphous casting by-product	5	
D3-20–08	Gun	Chase fragment	18	Part of the trunnion ring and the chase astragal and fillets are preserved, with decoration (mermaids and acanthus leaves)
D3-20–09	Gun	Barrel fragment	74	Probably part of the chase, associated with an amorphous casting by-product
D3-20–10	Gun	Barrel fragment	38	
D3-20–11	Gun	Chase fragment	28	Presents similar features to specimen D3-20–08
D3-20–14	Gun and lump	Barrel fragments (3) welded together by an amorphous casting by-product	214	The larger fragment shows a change in the wall's thickness possibly associated with a reinforced transition

regard, the identification of their traits (e.g. design, decoration, and marks) was constrained by the fragmentary and irregular aspect of most pieces (see below). Aiming to develop a technological assessment, a total of thirteen pieces comprising gun remains and casting by-products were selected for microstructural and chemical analyses (Table 1).

Characterisation methods and techniques

Macroscopic exam

An examination of the main characteristics of the bronze remains retrieved from the Delta III site was developed by visual inspection. For guns, in particular, the aim was to identify a series of features to appraise their type, provenance, and period. The ornamentation of some less fractured pieces was also valuable for assessing the style of a particular founder or atelier. The observed features in the guns' fragments and the amorphous casting by-products helped to determine the most likely nature of the recovered scraps. The sampling for the materials' characterisation was done based on this preliminary non-destructive testing.

Microscopic and chemical analysis

For guns, two different groups were defined for sampling. The remains exhibiting heterogeneous attributes associated with a failed casting, including welded amorphous by-products ($n = 6$), were analysed in two to four different areas to examine their material characteristics. On the other hand, small pieces that did not present significant observable differences ($n = 6$) were sampled in one place only. An isolated amorphous by-product was also studied separately.

The samples were studied applying the following methods and techniques: metallographic examination by light microscopy (LM) and scanning electron microscopy (SEM); and elemental composition analysis using energy dispersive X-ray spectroscopy (EDX), for major and minor constituents, the latter in a concentration above 0.1%. The used instrumentation, respectively, were an inverted metallographic microscope Leica DMi8 A and a FEI Nova NanoSEM 450 with EDAX. Statistical analysis of compositional data was carried out with XLSTAT software.

Specimens were prepared and analysed following international standards (e.g. Vander Voort 2004). For LM, samples were obtained using a common hacksaw and a Dremel 300 Series with abrasive cutting discs. Each specimen was

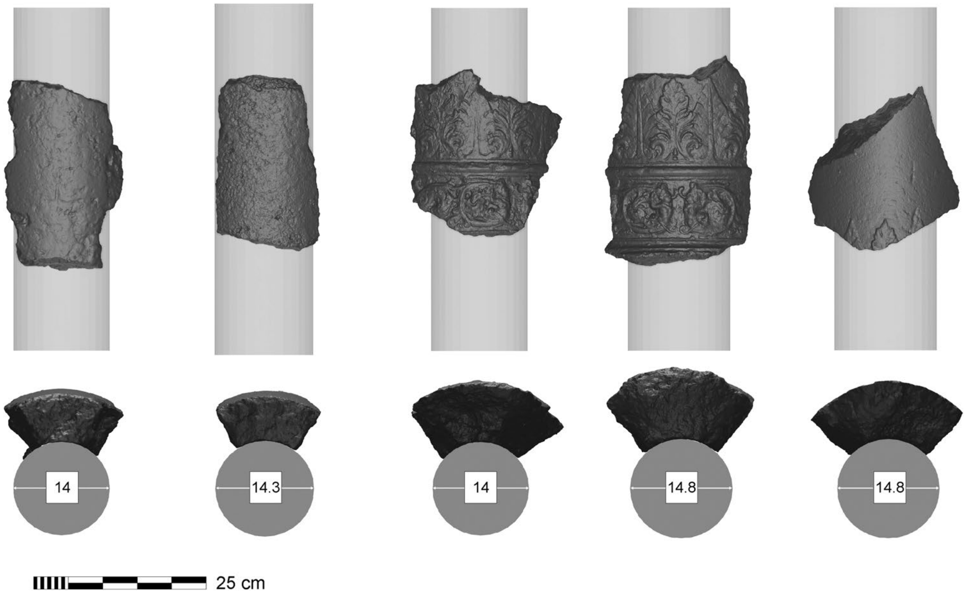

Fig. 2 Bore diameter estimation (in cm) of some of the larger and better-preserved barrel fragments (left to right: gun nos. D3-20–3, D3-20–4, D3-20–8, D3-20–11, and D3-20–12). Image: E Fernández Tudela

embedded in resin and its surface was ground and polished with a Tegramin 30 automatic equipment. For SEM–EDX, specimens were observed on polished areas of the core material that show no corrosion. Images based on secondary and backscattered electrons were obtained, the latter to assess the composition differences of the alloy microconstituents. For semi-quantitative analysis of major and minor elements (above 1 wt%), a minimum of five spot measures (at a × 250 magnification) were developed in each specimen. Point determinations and elemental distribution maps were also produced to characterise the different phases and microconstituents of the materials' microstructure.

Moreover, the liquidus temperature (LT) of the material of five specimens was determined using Thermo-Calc Software (v. 2023a) and the TCCU5 thermodynamic and properties database for Cu-based alloys.

Results

Classification, design, decoration, and marks of guns

The remains from the Delta III site seem to correspond either to culverins or, most likely, cannons (see below). A range of calibres from about 18 to 24 pounds was roughly estimated based on the preserved bore radial segments of the larger and better-preserved (non-deformed) barrel fragments. Their diameters range from ca. 140 to 148 mm (Fig. 2).

From the whole collection, only nine samples show decorative floral motifs on their surface, with prevailing Renaissance/Baroque acanthus leaf linear moulding. These leaves form two main patterns: isolated and differently spaced from each other; and alternated with lanceolate or rounded leaves, in a frieze design. The first decoration was recorded in the breech ogee of two specimens, nos. SP-082 and DIII-847 (pattern no. 1), and the second, was observed in areas most likely corresponding to the chase and muzzle of six pieces, nos. SP-117, DIII-822, DIII-838, D3-20–8, D3-20–11, and D3-20–12 (pattern no. 2). Combined with the latter, a third decoration consists of figurative motifs, also forming a frieze design, which is displayed between the second reinforce-ring and ogee and the chase astragal of pieces nos. DIII-838, D3-20–8, and D3-20–11 (pattern no. 3). A single piece of this assemblage (no. DIII-834) is distinguished by a decoration with military motifs (a gun with its carriage, and pikes or flagpoles for banners) at the end of the chase, just before the muzzle astragal and fillets (pattern no. 4).

Gun no. DIII-847 is the largest piece recovered from the site, with a length of 118 cm. The remains comprise about two-thirds of a complete gun: the chase, cascable, dolphins, and right trunnion, are not preserved (broken/miscast). However, the recorded features—some showed by other guns' fragments—allowed us to circumscribe its origin and date. The breech ogee is decorated with a series of acanthus leaves finishing with an accused scroll (pattern no. 1). The touch-hole is recessed in a square-shaped vent pan and an emblem is observed between the vent astragal and fillets and the first reinforce-ring and ogee. The latter encompasses a castle with three towers, with a cross on top of the central one and a Marian star on each side tower; in the upper part, it has a crested helmet, three peacock feathers, six banners of arms, and mantling; and it is all surrounded by olive branches (Fig. 3). This emblem corresponds to one of the variants of the coat of arms of the Free and Hanseatic City of Hamburg

Fig. 3 Image of gun No. DIII-847: **a** detail of the coat of arms; and **b** drawing of the middle coat of arms of Hamburg (Mittleres Wappen der Freien und Hansestadt Hamburg, from: https://www.wikiwand.com/de/Landeswappen_Hamburgs). Image: NC Ciarlo

(i.e. middle arms, *Mittleres Wappen*), suggesting the gun was an express order to the city for defence or parade/salute purposes.

The signature of particular Renaissance gunfounders or their workshops was usually well represented in the design of gun breeches—along with the features of other decorative motifs—which were transmitted with minor or major changes from one generation to another (see López-Martín 2011:324–330, 342–352). The breech design and decoration and other attributes of gun no. DIII-847 show similarities with pieces cast by German bell and cannon founders of the renowned atelier established by Matthias Benningk (also, Benning or Benninck) in the Free and Hanseatic City of Lübeck, north of Germany (see Kennard 1986:40). A common trait in various bronze guns cast by the sons of Reinhard Benningk, Gerdt (1601–1643) and Hermann (the Elder, 1618–1668), is a pineapple-like cascable, yet this part was not preserved in the studied gun. Albert Benningk (1637–1695), the son of the latter, was also a prominent founder that slightly changed this particular design on their guns (López-Martín 2011:349–350).

Other characteristics of guns from Benningk's workshop can also be suggestive (Fig. 4). A bronze 6-pdr gun cast by Hermann the Elder in Lübeck (1643) and located at the Armémuseum (gun no. AM.010003, also A-189), in Stockholm, has a breech ogee decoration, vent pan, and dolphins similar to those observed in gun no. DIII-847. There is another piece made by this founder in 1662, a bronze 12-pdr gun nowadays displayed at the Museum for Hamburg History (Museum für Hamburgische Geschichte, gun no. 1911, 548), in Hamburg. It shows the coat of arms of Hamburg along with six coats of arms of the civilian delegates in charge of the towns' artillery (so-called *Artillerie-herren*) in the first reinforce and also has a comparable breech. A quite similar Benningk's gun, also cast in 1662, is at the Royal Artillery Museum (former Firepower Museum), in Larkhill,

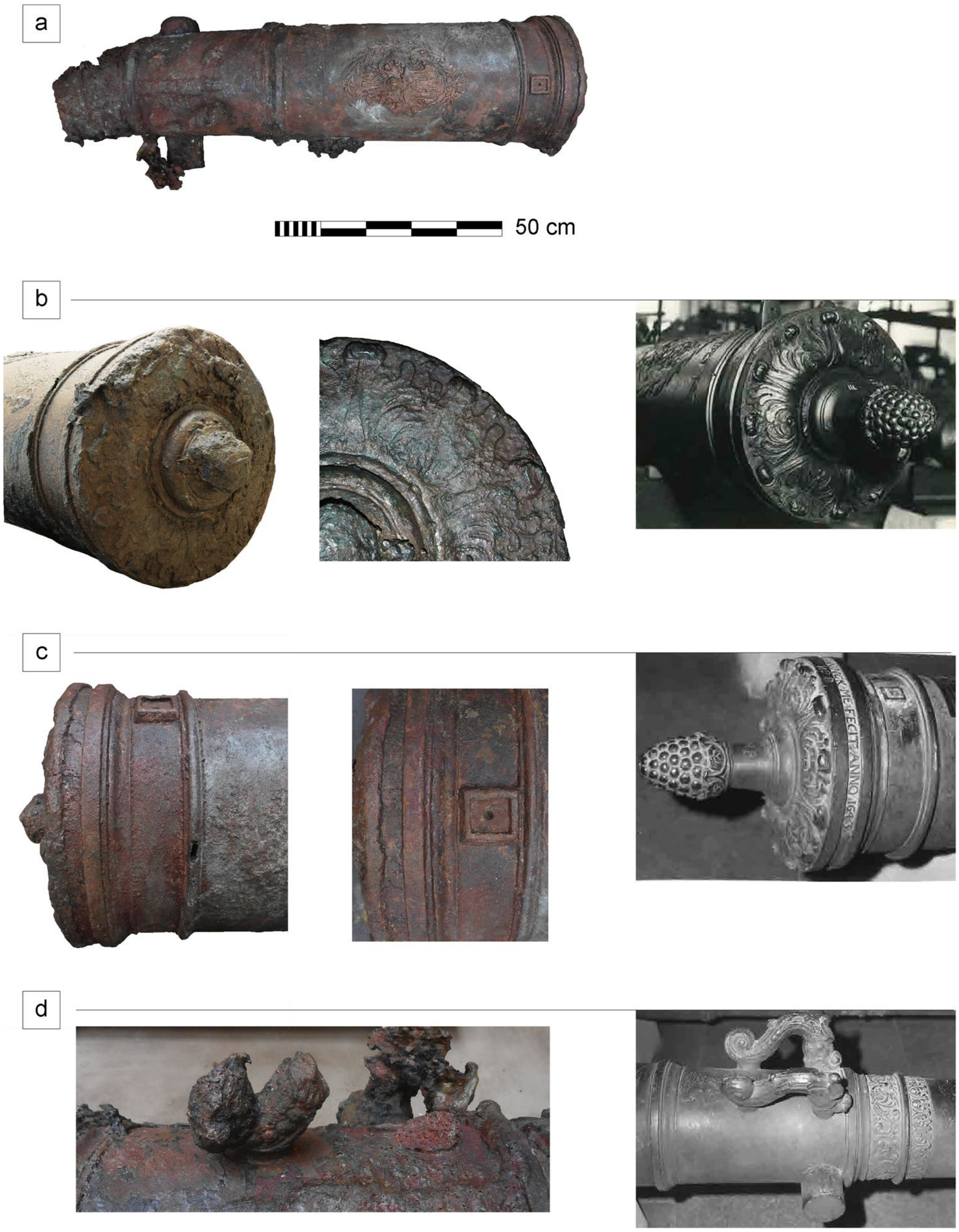

Fig. 4 A comparison of piece no. DIII-847 with mid-seventeenth-century German bronze guns: **a** general view of the gun; **b** decorative motifs of the breech ogee (left and centre) and gun no. 116, Royal Danish Arsenal Museum (Peterson 2014b:74) (right); **c** views of the breech and vent pan (left and centre) and gun no. AM.010003, Swedish Army Museum (Peterson 2014b:405) (right); and **d** detail of the tail of the right dolphin (left) and gun no. AM.010003 (Peterson 2014b:406) (right). Image: NC Ciarlo and J Martí Solano

UK (gun no. II-159). Other attributes shared by both pieces attest to certain stylistic continuity for at least two decades. Moreover, this kind of breach is exhibited by a 12-pdr gun (unidentified founder), that displays the name of Christian Albrecht together with the coats of arms of the Holstein-Gottorp dukes and bishopric of Lübeck, located at the Royal Danish Arsenal Museum (Tøjhusmuseet), in Copenhagen (gun no. 116) (see Peterson 2014a, pp. 315–317, 882; 2014b, pp. 74–77, 405–406).

The second and third decorative patterns were recorded together in three barrel fragments of comparable characteristics (nos. DIII-838, D3-20–8, D3-20–11). The anthropomorphic figures resemble mermaids, which are paired in a specular position, i.e. facing each other. Similarities in their design suggest they could proceed from the same workshop (Fig. 5). A 12-pdr bronze gun located at the Armémuseum (unidentified founder) has decorative motifs at the second reinforce-ring and ogee and the muzzle astragal and fillets that resemble the mentioned decoration. The name "Sophia Amalia" is placed below a coat of arms at the first reinforce. The dolphins, breach, and cascable of this gun are also comparable with the traits of the studied pieces (Peterson 2014b:339–341).

Motifs depicted in gun no. DIII-834 at the end of the chase (pattern no. 4) are rather unclear given the irregular surface finishing. However, a resemblance with the decoration shown by the *Pallas*, a 24-pdr bronze gun cast by Albert Benningk in Lübeck (1679) and located at the

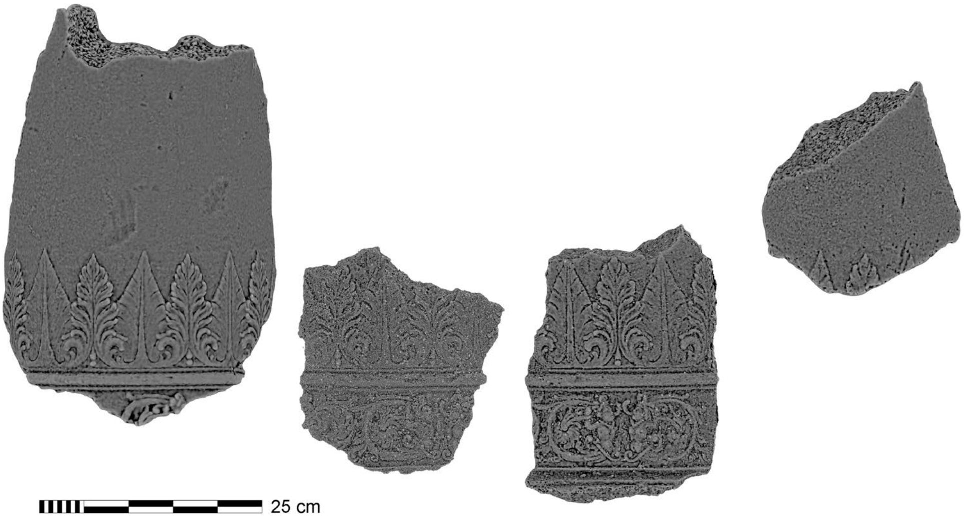

Fig. 5 3D models of guns: front view of four -barrel pieces showing decoration patterns nos. 2 and 3 (left to right: gun nos. DIII-838, D3-20–8, D3-20–11, and D3-20–12). Image: E Fernández Tudela

German History Museum (Deutsche Historische Museum), in Berlin, is noticeable (Peterson 2014a:865–866).

Defects: surface examination

In general, pieces show some degree of porosity, mostly pinholes concentrated at the surface or in a layer just below it. Shrinkage cavities or pipes were also recorded in a few samples. Possible misruns were not seen but in one gun (e.g. dolphins of gun no. DIII-847). Cracks (hot tears[5] and cold tears) and veining were observed, but they are not common defects. Sponginess (or honeycombing) was also recorded in several gun fragments. Some deformation could be appreciated in barrel fragments as well (e.g. oval-shaped bores). At least one piece also exhibits clear signs of extensive vitrification. Amorphous by-products appear in isolation and as well as welded to guns' parts, usually with encrusted charcoal remains (Figs. 6 and 7). All these features are associated with a failed casting. The microstructural and chemical characterisation of selected specimens provided further data in this regard (see below).

Only a minor quantity of the assemblage shows no clear evidence of severe casting defects. Despite being fragmented and having veining, no porosity, cracks, deformation, misruns, or sponginess, among other defects, were noticed (Fig. 7k). They might correspond either to fractured old guns or to discarded partially well-cast products. One of these remnants (no. D3-20–02) was also analysed for comparative purposes.

Material characterisation

The gun remains and casting by-products (isolated and linked to barrel parts) from the Delta III site selected for metallurgical examination were described in Table 1. At a microstructural level, analysed specimens show an as-cast microstructure, with no evidence of further thermo-mechanical alteration. The matrix is composed either of a uniform, single alpha (α) phase fcc grains (a solid solution of tin dissolved in copper) or, as was observed in most cases, a copper-rich α phase with different amounts of a tin-rich eutectoid alpha + delta (α + δ) phase distributed at the boundaries of the copper-rich grains (Fig. 8 a to e). The harder and less ductile δ phase is transformed from the α phase in bronzes with tin content above ca. 11% (Nielsen 2019). Although, in practice, the tin-rich eutectoid occurs in bonzes with a much less percentage, given the micro-segregation of tin during the non-equilibrium solidification (Pero-Sanz Elorz 2000:216–217; Murphy 2001:76; Scott and Schwab 2019:146).

This α + δ phase was observed in both guns' fragments and amorphous by-products with a tin content as low as 1.5% (specimen DIII-847, specimen #3), but in a large degree in samples above ca. 2–3%. Moreover, a thin outer layer (ca. 1 mm thick) with a high content of tin was detected in droplets (specimens DIII-835_#3 and #4). The copper, tin, and lead particular distribution in the microstructure of samples was observed by a mapping analysis (Fig. 9). Given its mechanical properties, the extensive α + δ phase patches present in amorphous by-products would have made this material unsuitable for guns (see Murphy 2001:91–92).

Samples have different microstructural characteristics linked to the solidification process (see Murphy 2001:91; Rajpitak 1983:74–76, for a description of microstructures of low-tin bronzes). In general, most gun barrels have a coarse as-cast microstructure, showing no coring, evidence

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[5] Hot tearing is also referred to as hot cracking, hot shortness, and hot brittleness (Campbell 2011:465).

Fig. 6 Macroscopic casting defects observed at the remains surface: **a** cracks: cold tear; **b** sponginess; **c** misrun (unfilled dolphin); **d** vitrification; **e** open shrinkage cavities or pipes; **f** mould collapse; **g** gas porosity: blowholes; **h** metal drops; **i** deformation; **j** charcoal incrustation; and **k** gas porosity: pinholes. Image: NC Ciarlo

related to a slow cooling process that allowed a homogenization of the cast (see Fig. 8 a and c). On the other hand, a dendritic and finer microstructure was observed in samples corresponding to by-products, which would have been subjected to a faster cooling rate (see Fig. 8e). An acicular structure associated with an even more quick solidification was also recorded in the outer layers of droplets (see Fig. 8f).

Fig. 7 A detailed view of macroscopic casting defects in a selection of pieces: **a** gas porosity: pinholes; **b** cracks: cold tear; **c** vitrification; **d** sponginess; **e** open shrinkage cavities or pipes; **f** mould collapse; **g** gas porosity: blowholes; **h** metal drops; **i** massive crack; **j** charcoal incrustation; and **k** veining (mould cracking?). Image: NC Ciarlo

Most samples present a third lead-rich phase as inclusions distributed at the grain boundaries, associated with the pools of tin-rich eutectoid. This content is also reflected in the overall composition of samples (see below). Moreover, evidence of gas and shrinkage porosity, mainly micro-pores and micro-shrinkage of different sizes, was observed in several

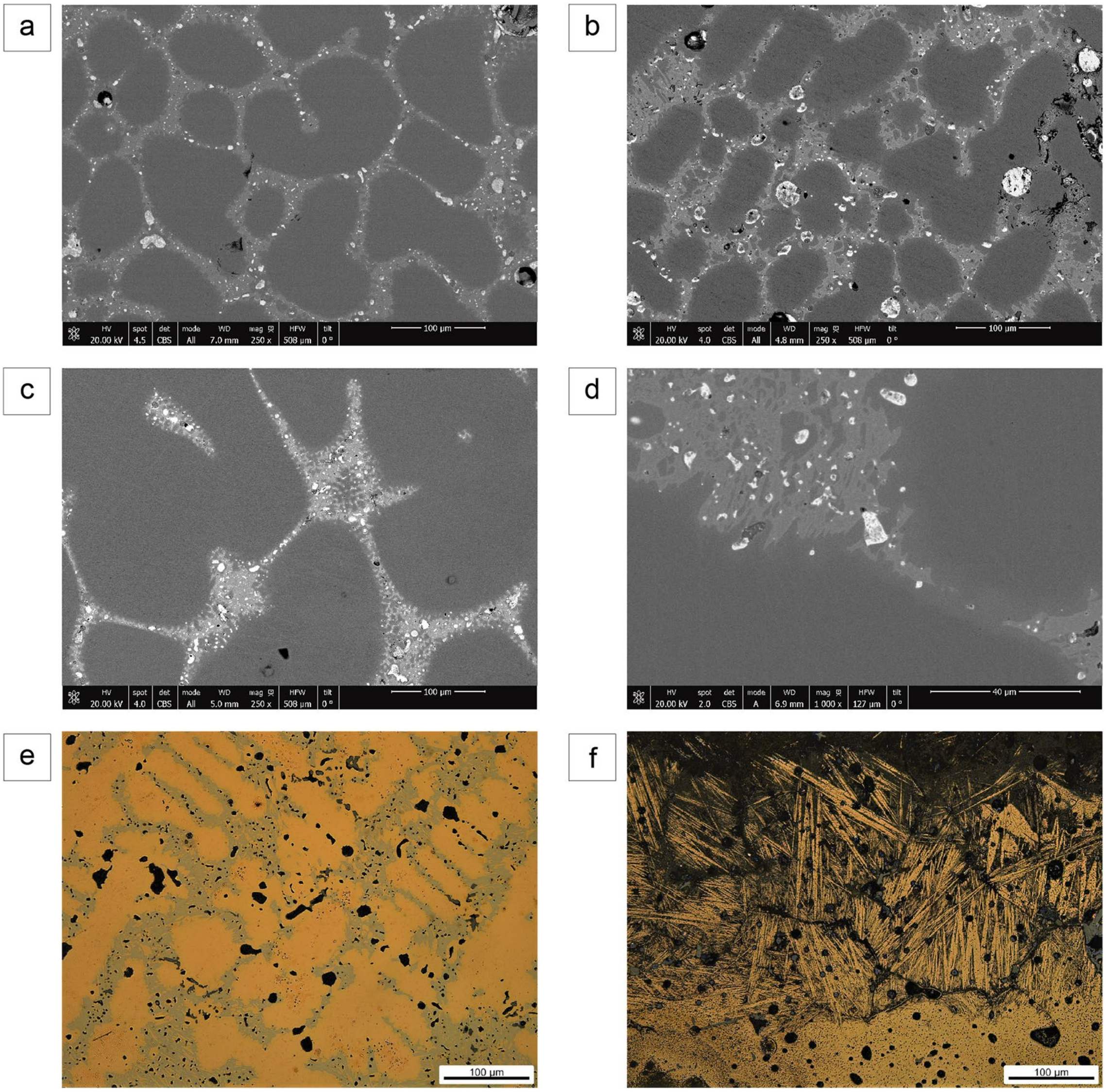

Fig. 8 As-cast bronze microstructures of an α-phase solid solution with intergranular pools of α + δ phases: (**a**–**d**) SEM images (BSE mode) of specimens DIII-835_#2, DIII-S/D_#2, DIII-847_#4, and D3-20-09_#1; and (**e**–**f**) LM photomicrographs of specimens D3-20-6_#2 and DIII-835_#3. Images: J González García (**a**-**d**) and NC Ciarlo (**e**-**f**)

remains. Gas porosity is associated with the evolution of oxygen and hydrogen absorbed from the furnace atmosphere (see Campbell 2011:310–311). Identified pores resulted in part from the evolving of these gases due to the decrease of their solubility during solidification, which could not escape freely. Moreover, extensive surface porosity observed through the outer layers of several gun barrel fragments is most likely related to the reaction of the hot metal and the moisture of the mould during pouring (Fig. 10 a and b). On the other hand, shrinkage porosity is generated by the contraction of the molten metal during solidification. This phenomenon usually occurs when molten metal is excessively hot and in the areas of the mould poorly fed (e.g. the gun's breech) (Murphy 2001:92–93). Although the lead content would have promoted a pressure-tight alloy, it has not sufficed to counteract the shrinkage porosity expected for long-freezing-range bronzes in sections above 50 mm thick (see Murphy 2001:78) (Fig. 10c to f).

The matrix elemental composition of specimens is summarized in Table 2. For each sample, individual results and means values are listed. Carbon and oxygen were not quantified.

The material used to cast the analysed guns was bronze with small amounts of lead. No zinc nor other minor elements were detected. A bar plot and binary diagram of the mean composition of samples depict the proportion of the main elements (Fig. 11). Based on a triangular plot of Cu, Sn, and Pb data, significant differences between gun barrel fragments and

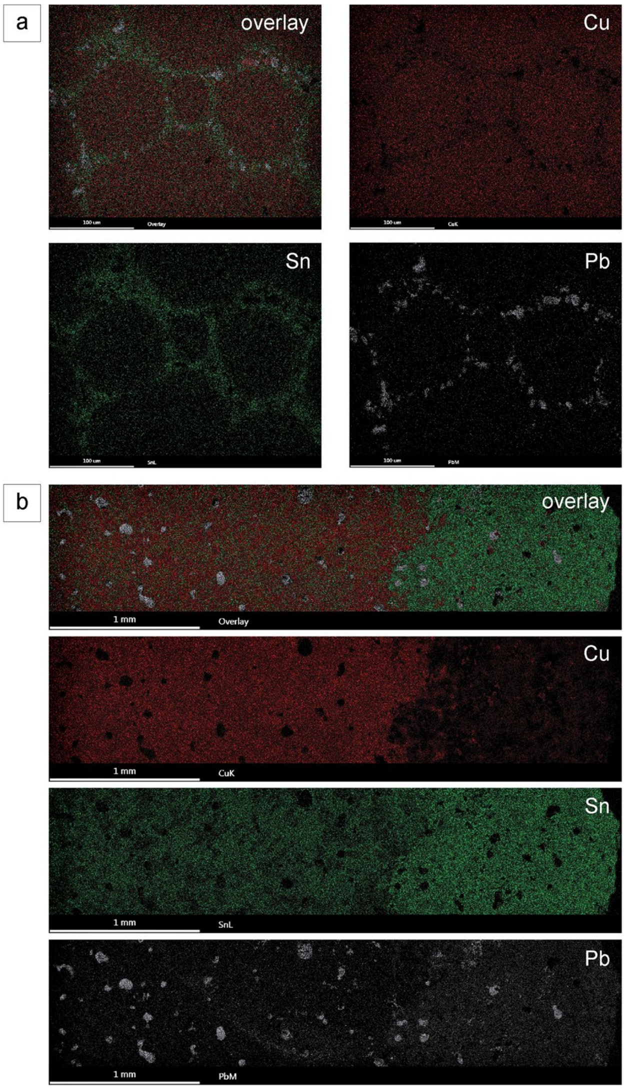

Fig. 9 EDX mapping of alloying elements: **a** Cu, Sn, and Pb distribution in the α and α + δ phases of specimen DIII-835_#5; and **b** Sn concentration at the outer layer of specimen DIII-835_#4. Images: J González García

casting by-products were observed, with a certain degree of overlapping. Moreover, as expected, the compositional range of gun remains shows a comparatively lower dispersion of values (Fig. 12). The similarities in the composition of gun nos. D3-20–04, D3-20–10, D3-20–8, and D3-20–11 are noteworthy; the latter two, in particular, show the same decorative pattern.

The values are relatively homogeneous within each metallographic specimen. However, differences in the matrix mean composition are appreciated both within each gun and more noticeably between barrel fragments, which have been made in bronzes ranging from about 1 to 6.5% tin and up to 2% lead. Moreover, a higher heterogeneity was recorded between these remains and the associated casting by-products. The latter also show notable differences if amorphous masses of bronze (mostly from ca. 8 to 13% tin and up to 4.5% lead) and droplets (ca. 16 to 19% tin and up to 5.5% lead) are compared to each other. Given the range of compositions, the gun remains and casting by-products (DIII-835_#1, DIII-835_#2, DIII-835_#3, DIII-847_#1, and D3-20-02_#1) also present dissimilar melting points. In general, the LT of guns' material is in the range of 1029 °C to 1081 °C, while the by-products are around 868 °C and 1017 °C.

A discussion, in the light of seventeenth-century European bronze guns

On classification, date, and provenance

Broadly speaking, smooth-bore guns used on ships dominated through the age of sail (Lavery 1987:83). Different genres were developed over time: culverins, cannons (or cannons of battery), and perriers (*pedreros*) comprise the three main genres of European bronze guns. Mortars were either included within the last genre or considered a separate one. This basic classification was established based on the length, calibre, and shot of pieces, as it is described in Collado's *Platica manual de artilleria* (1592) and illustrated in Sardi's treatise *L'artiglieria* (1621) (Fig. 13a). Along with a regional variation, a diversity of guns can be appreciated within each type. This situation prevailed until the mid-to-late seventeenth century when artillery was progressively standardised (see Meide 2002:1–6) (Fig. 13b).

Bronze guns stood as both high-technology weapons and works of art, expensive sculptures which stood as vehicles of power and wealth (see López-Martín 2011). They were usually profusely decorated, exhibiting a wide diversity of motifs on their surface. Along with the moulded rings (i.e. reinforces' ring and ogees; and the vent, chase, and muzzle astragal and fillets), they showed other traits such as a pair of lifting handles known as dolphins; floral patterns (e.g. acanthus leaf) or abstract decoration in relief; the gun's name; and meaningful phrases (Meide 2002:16–30). In general, a progressive simplification of ornamental motifs was developed over time seeking to save time and increased production.

Along with aesthetic features, bronze guns frequently show other marks, such as the date of manufacture, calibre, weight, founder's name, ruler's coats of arms or monogram, cypher or armorial device of the Master-General of the Ordnance (or alike). Together with later proof marks, they can provide valuable data about the biography of each object and its context. Several seventeenth-century bronze guns associated with wreck sites and displayed at museums attest to this complex decoration and marking practice (e.g. Keith et al.

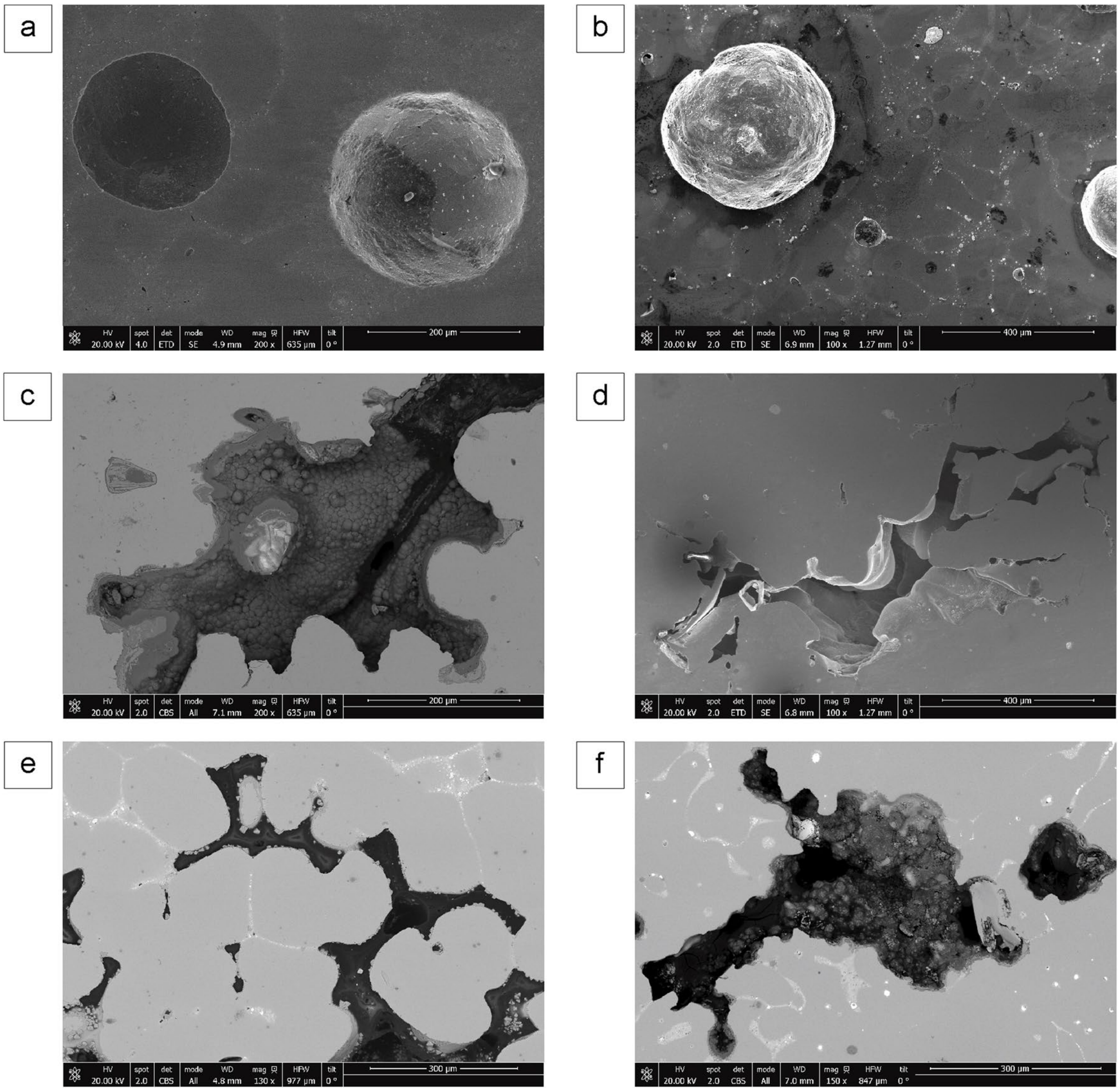

Fig. 10 A selection of SEM images (SE and BSE modes) showing microstructural defects: (**a**, **b**) gas micro-porosity in specimens DIII-S/D_#3 and DIII-835_#2; and (**c**–**f**) micro-shrinkage porosity in specimens D3-20-04_#1, D3-20-10_#1, D3-20-09_#1, and D3-20-11_#1, respectively. Images: J González García

1997; Ortiz Sotelo 2012–2013; Peterson 2014a, b; Oliver Laso and Ramírez Pernía 2021).

As pieces from the Delta III site are concerned, their design, decoration, and marks suggest they were likely cast by a member of Benningk's family around the second or third quarter of the seventeenth century. Other remains recovered from the Delta III site were also identified as of German origin, such as an assembly of crucibles from Hesse (González Gallero 2023). As was referred to above, the shipwreck was identified as a mid-to-late seventeenth-century Dutch merchantman.

The Dutch-Flemish merchants played an active commercial role in Southern Spain and the Hispanic-American trade system during this period and thereafter, using the port city of Cadiz as a nexus point with overseas territories in the Americas (Crespo Solana 2014). Aguilar Escobar (2008) demonstrates that a large part of the demand for raw material to the Royal Artillery Factory of Seville (*Real Fábrica de Artillería de Sevilla*) throughout the seventeenth and eighteenth centuries was fulfilled with old bronze (*metal ligado* or *bronce viejo*) from useless guns or failure castings. Moreover, at Seville was settled the Habet family, of German origin, which obtained a large contract with the Spanish government from 1650 to 1717 to supply copper from the Americas and Europe (González Enciso 2013:291; see also Aguilar Escobar 2008, for further data on Habet's family business). That the old bronze from the Delta III site was meant for this local market and foundry should be taken into consideration.

Table 2 EDX data (wt%) of main and minor alloying elements of analysed guns and casting by-products. The mean and standard deviation (σ) of values are referred to in bold. Percentages of copper were rounded to the nearest whole number, and minor elements to one decimal place

Object ID_EDX spot number	Specimen #1			Specimen #2			Specimen #3			Specimen #4		
	Cu	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**
DIII-835	Barrel (inner layer)			By-product (amorphous mass)			By-product (droplet)			By-product (droplet)		
DIII-835 (1)	96	3.8	0.6	91.1	7.3	1.6	67.3	24.6	8.1	81.6	16.4	2.1
DIII-835 (2)	94	4.6	1.4	91.0	7.4	1.7	81.9	14.1	4.1	80.5	16.6	2.9
DIII-835 (3)	95	4.0	1.0	89.1	8.9	2.1	71.1	23.5	5.4	80.2	16.3	3.4
DIII-835 (4)	94	4.7	1.4	90.5	7.9	1.6	78.9	15.3	5.8	80.7	16.2	3.2
DIII-835 (5)	95	4.3	0.9	87.8	9.4	2.8	78.3	17.3	4.4	79.0	16.8	4.2
DIII-835 (mean)	**95**	**4.3**	**1.1**	**89.9**	**8.2**	**1.9**	**75.5**	**18.9**	**5.6**	**80.4**	**16.5**	**3.2**
DIII-835 (σ)	**0.6**	**0.4**	**0.3**	**1.3**	**0.8**	**0.4**	**5.4**	**4.3**	**1.4**	**0.8**	**0.2**	**0.7**
DIII-847	Chase (outer layer)			Chase (inner layer)			Chase (inner layer)			Chase (inner layer)		
DIII-847 (1)	99	0.8	n.d	93.5	5.3	1.2	98.6	1.0	0.4	96.4	3.1	0.6
DIII-847 (2)	99	1.2	n.d	94.1	5.0	1.0	98.0	1.6	0.5	95.9	3.4	0.6
DIII-847 (3)	100	0.0	n.d	90.5	7.5	2.0	98.2	1.4	0.4	95.4	4.0	0.6
DIII-847 (4)	99	0.8	n.d	94.4	5.0	0.6	98.0	1.4	0.5	96.1	3.6	0.4
DIII-847 (5)	99	1.1	n.d	94.6	4.6	0.8	97.8	1.8	0.4	95.6	3.7	0.7
DIII-847 (mean)	**99**	**0.7**	**n.d**	**93.4**	**5.5**	**1.1**	**98.1**	**1.5**	**0.4**	**95.9**	**3.6**	**0.6**
DIII-847 (σ)	**0.4**	**0.4**	**0.0**	**1.5**	**1.0**	**0.5**	**0.3**	**0.3**	**0.0**	**0.3**	**0.3**	**0.1**
DIII-S/D	Chase (outer layer)			By-product (amorphous mass)			By-product (amorphous mass)					
DIII-S/D (1)	94	4.8	1.3	86.2	10.5	3.3	88.3	9.3	2.5	-	-	-
DIII-S/D (2)	94	5.0	1.3	86.7	10.0	3.3	89.5	8.1	2.4	-	-	-
DIII-S/D (3)	93	5.7	1.3	85.7	10.1	4.2	87.8	8.8	3.4	-	-	-
DIII-S/D (4)	95	4.5	0.9	87.1	10.3	2.6	88.4	8.4	3.2	-	-	-
DIII-S/D (5)	92	6.5	1.8	87.3	10.5	2.2	87.5	9.6	2.9	-	-	-
DIII-S/D (mean)	**93**	**5.3**	**1.3**	**86.6**	**10.3**	**3.1**	**88.3**	**8.8**	**2.9**	-	-	-
DIII-S/D (σ)	**1.0**	**0.7**	**0.3**	**0.6**	**0.2**	**0.7**	**0.7**	**0.5**	**0.4**	-	-	-
D3-20–01	Muzzle (inner layer)			Muzzle (bore)								
D3-20–01 (1)	94	4.2	1.8	93.9	4.7	1.5	-	-	-	-	-	-
D3-20–01 (2)	96	2.8	0.8	93.8	4.7	1.5	-	-	-	-	-	-
D3-20–01 (3)	95	4.1	1.3	94.1	4.6	1.3	-	-	-	-	-	-
D3-20–01 (4)	95	4.0	1.4	91.9	5.8	2.3	-	-	-	-	-	-
D3-20–01 (5)	95	3.7	0.9	92.7	5.3	2.1	-	-	-	-	-	-
D3-20–01 (mean)	**95**	**3.8**	**1.2**	**93.3**	**5.0**	**1.7**	-	-	-	-	-	-
D3-20–01 (σ)	**0.8**	**0.5**	**0.4**	**0.9**	**0.5**	**0.4**	-	-	-	-	-	-
D3-20–02	2nd reinforce (outer layer)											
D3-20–02 (1)	90	7.7	2.6	-	-	-	-	-	-	-	-	-

Table 2 (continued)

Object ID_EDX spot number	Specimen #1			Specimen #2			Specimen #3			Specimen #4		
	Cu	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**
D3-20–02 (2)	91	6.1	3.3	-	-	-	-	-	-	-	-	-
D3-20–02 (3)	92	6.8	1.0	-	-	-	-	-	-	-	-	-
D3-20–02 (4)	92	6.3	1.7	-	-	-	-	-	-	-	-	-
D3-20–02 (5)	92	6.5	1.9	-	-	-	-	-	-	-	-	-
D3-20–02 (mean)	**91**	**6.7**	**2.1**	-	-	-	-	-	-	-	-	-
D3-20–02 (σ)	**1.0**	**0.6**	**0.8**	-	-	-	-	-	-	-	-	-
D3-20–03	Barrel (bore, a burr)											
D3-20–03 (1)	85	12.4	2.2	-	-	-	-	-	-	-	-	-
D3-20–03 (2)	89	9.3	1.5	-	-	-	-	-	-	-	-	-
D3-20–03 (3)	83	13.7	2.9	-	-	-	-	-	-	-	-	-
D3-20–03 (4)	84	13.3	2.8	-	-	-	-	-	-	-	-	-
D3-20–03 (5)	83	13.5	3.5	-	-	-	-	-	-	-	-	-
D3-20–03 (mean)	**85**	**12.4**	**2.6**	-	-	-	-	-	-	-	-	-
D3-20–03 (σ)	**2.3**	**1.7**	**0.7**	-	-	-	-	-	-	-	-	-
D3-20–04	Barrel (outer layer)											
D3-20–04 (1)	93	5.8	0.8	-	-	-	-	-	-	-	-	-
D3-20–04 (2)	93	6.5	0.3	-	-	-	-	-	-	-	-	-
D3-20–04 (3)	94	5.7	0.3	-	-	-	-	-	-	-	-	-
D3-20–04 (4)	94	5.8	0.3	-	-	-	-	-	-	-	-	-
D3-20–04 (5)	93	5.8	0.8	-	-	-	-	-	-	-	-	-
D3-20–04 (mean)	**94**	**5.9**	**0.5**	-	-	-	-	-	-	-	-	-
D3-20–04 (σ)	**0.3**	**0.3**	**0.2**	-	-	-	-	-	-	-	-	-
D3-20–06	By-product (amorphous mass)											
D3-20–06 (1)	83	12.6	4.7	-	-	-	-	-	-	-	-	-
D3-20–06 (2)	84	12.8	3.5	-	-	-	-	-	-	-	-	-
D3-20–06 (3)	81	14.1	5.0	-	-	-	-	-	-	-	-	-
D3-20–06 (4)	82	12.0	5.7	-	-	-	-	-	-	-	-	-
D3-20–06 (5)	82	13.3	4.3	-	-	-	-	-	-	-	-	-
D3-20–06 (mean)	**82**	**13.0**	**4.6**	-	-	-	-	-	-	-	-	-
D3-20–06 (σ)	**0.9**	**0.7**	**0.7**	-	-	-	-	-	-	-	-	-
D3-20–08	Chase (bore)											
D3-20–08 (1)	93	5.7	1.5	-	-	-	-	-	-	-	-	-
D3-20–08 (2)	93	6.1	0.6	-	-	-	-	-	-	-	-	-
D3-20–08 (3)	94	5.8	0.5	-	-	-	-	-	-	-	-	-
D3-20–08 (4)	93	5.9	1.1	-	-	-	-	-	-	-	-	-

Table 2 (continued)

Object ID_EDX spot number	Specimen #1			Specimen #2			Specimen #3			Specimen #4		
	Cu	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**	**Cu**	**Sn**	**Pb**
D3-20–08 (5)	94	6.1	0.4	-	-	-	-	-	-	-	-	-
D3-20–08 (mean)	**93**	**5.9**	**0.8**	-	-	-	-	-	-	-	-	-
D3-20–08 (σ)	**0.3**	**0.2**	**0.4**	-	-	-	-	-	-	-	-	-
D3-20–09	Chase (surface, a burr)			Chase (inner layer)			Chase (outer layer)					
D3-20–09 (1)	93	5.6	1.0	96.2	3.0	0.8	97.8	2.0	0.2	-	-	-
D3-20–09 (2)	93	6.0	1.4	97.1	2.4	0.5	97.8	2.0	0.2	-	-	-
D3-20–09 (3)	93	5.5	1.2	97.6	2.0	0.4	97.8	2.0	0.2	-	-	-
D3-20–09 (4)	91	7.0	2.2	97.1	2.4	0.5	97.5	2.4	0.2	-	-	-
D3-20–09 (5)	94	5.3	1.2	97.8	1.8	0.4	97.3	2.2	0.4	-	-	-
D3-20–09 (mean)	**93**	**5.9**	**1.4**	**97.2**	**2.3**	**0.5**	**97.6**	**2.1**	**0.2**	-	-	-
D3-20–09 (σ)	**1.0**	**0.6**	**0.4**	**0.6**	**0.4**	**0.1**	**0.2**	**0.2**	**0.1**	-	-	-
D3-20–10	Barrel (outer layer)											
D3-20–10 (1)	93	6.0	0.9	-	-	-	-	-	-	-	-	-
D3-20–10 (2)	94	6.0	0.3	-	-	-	-	-	-	-	-	-
D3-20–10 (3)	94	5.8	0.7	-	-	-	-	-	-	-	-	-
D3-20–10 (4)	94	6.2	0.0	-	-	-	-	-	-	-	-	-
D3-20–10 (5)	93	6.1	0.6	-	-	-	-	-	-	-	-	-
D3-20–10 (mean)	**94**	**6.0**	**0.5**	-	-	-	-	-	-	-	-	-
D3-20–10 (σ)	**0.3**	**0.1**	**0.3**	-	-	-	-	-	-	-	-	-
D3-20–11	Chase (bore)											
D3-20–11 (1)	93	6.3	0.7	-	-	-	-	-	-	-	-	-
D3-20–11 (2)	92	7.0	0.9	-	-	-	-	-	-	-	-	-
D3-20–11 (3)	93	6.4	0.5	-	-	-	-	-	-	-	-	-
D3-20–11 (4)	93	6.4	0.7	-	-	-	-	-	-	-	-	-
D3-20–11 (5)	94	5.5	0.4	-	-	-	-	-	-	-	-	-
D3-20–11 (mean)	**93**	**6.3**	**0.6**	-	-	-	-	-	-	-	-	-
D3-20–11 (σ)	**0.7**	**0.5**	**0.2**	-	-	-	-	-	-	-	-	-
D3-20–14	2nd reinforce (inner layer)			1st reinforce (outer layer)			By-product (amorphous mass)					
D3-20–14 (1)	95	4.4	0.5	95.1	4.3	0.7	95.1	4.3	0.6	-	-	-
D3-20–14 (2)	95	4.4	0.3	93.1	3.3	3.6	97.1	2.4	0.4	-	-	-
D3-20–14 (3)	93	6.4	0.6	92.0	4.9	3.1	97.1	2.6	0.3	-	-	-
D3-20–14 (4)	96	4.2	0.3	93.8	4.6	1.6	97.4	2.3	0.3	-	-	-
D3-20–14 (5)	95	4.6	0.3	94.8	4.8	0.5	98.1	1.8	0.1	-	-	-
D3-20–14 (mean)	**95**	**4.8**	**0.4**	**93.7**	**4.4**	**1.9**	**97.0**	**2.7**	**0.3**	-	-	-
D3-20–14 (σ)	**0.9**	**0.8**	**0.1**	**1.1**	**0.6**	**1.2**	**1.0**	**0.9**	**0.2**	-	-	-

The gunfounding process

Given each piece was cast in an individual mould, every bronze gun was indeed unique—notwithstanding, quite similar "serial" pieces were produced by particular gunfounders using a single wooden template (see López-Martín 2011:361–362). In *Pirotechnia*, Vannoccio Biringuccio (1540) made a technical description of the gunfounding process as nobody previously had done before, providing guidelines for making bronze guns as fine as possible.[6] Until the nineteenth century, three other works are worth mentioning. The throughout-illustrated study of Pierre Surirey de Saint-Remy, first published in 1697, stand out (Saint-Remy 1707). It was the basis for the classical Diderot's *Encyclopédie* contribution on "Fonderie des Canons" (Diderot and d'Alembert 1767). In the late-eighteenth century, the French mathematician Gaspard Monge also published a technical treatise on gunfounding (Monge 1793–1794). The described methods to cast hollow guns differ little in essence (Murphy 2001:85).

Accounts on the moulding and casting processes were developed by combining data from documentary sources and archaeological evidence (e.g. Guilmartin 2005; Barker 1983; Keith et al. 1997; Keith and Rodriguez 2001; Kennard 1986; Murphy 2001; Hoskins 2003; López-Martín 2011). Casting a bronze gun was a highly skilled practice that comprised several interdependent phases, involving important technical operations. The success of the whole relied on the strict accomplishment of every step, which is summarized below.[7]

Preparation of the pattern and mould (step 1)

Guided by a drawing of the gun to be obtained, a full-sized pattern or model of the gun (i.e. the positive) was carefully built in wood or clay. If not all were made of wood, it was advisable to use a thick tapered wooden spindle which was wound around with rope and coated with several layers of clay or another suitable compound to achieve the desired thickness. Once dried, the trunnions, dolphins, ornaments (cornices and rings), and other decorations made of clay or wax were added to its surface and removed when the spindle was drawn out. At this phase, a full-size template or strickle board helped to obtain a uniform profile (Fig. 14, items A to E).

The mould was made around the model, first covering it with ashes or a fatty substance for acting as a demoulding agent (e.g. tallow), and then applying a coat of fine loam to guarantee the fidelity of the product's outer details, which was enlarged by several layers of fine quality clay that resist the fire well.[8] The exterior coatings were reinforced with iron wires, rods, and bands, also covered with clay. After drying, the pattern was removed from the inside, and the gates and vents were drilled at the feeding head (casting bell). The mould was elaborated in three or more separated parts, joined together: one for the body (the jacket or principal mould), one for the breech-cascable (it closed the mould at the bottom), and one for the bore (the core, attached inside with chaplets). Each part was individually baked with charcoal or wood, any crack was replastered, and the mould's inside was cleaned with care and covered with ashes (Fig. 14, items F to Q). Guaranteeing an adequate strengthening and drying of the mould was of most critical importance.

Turn on the kiln and melting of the alloy (step 2)

This process was developed in reverberatory furnaces using charcoal as fuel. Fine copper and tin (unalloyed) were melted and mixed. Also, bronze from scrap pieces and a minor amount of other metal elements could be added (see below). The type of bronze was defined according to the proportions (by weight) of fine metals. If old bronze was supplemented, a rough estimation based on the expected composition of each type of artefact was done. A test to assess the quality of the molten metal could be carried out and an adjustment of the ratio of metals developed if needed. A critical aim was to achieve a complete and homogeneous melting with the desirable quality.

Pouring the molten bronze and cooling (step 3)

The mould was placed in an upright position and breech-down in a pit at the foot of the furnace, where it was buried with rammed earth.[9] There, it was fed through a reservoir chamber placed above the muzzle (i.e. the feeding head), which received the molten metal through a pouring channel (Fig. 15). Once it was filled beyond the muzzle, the addition

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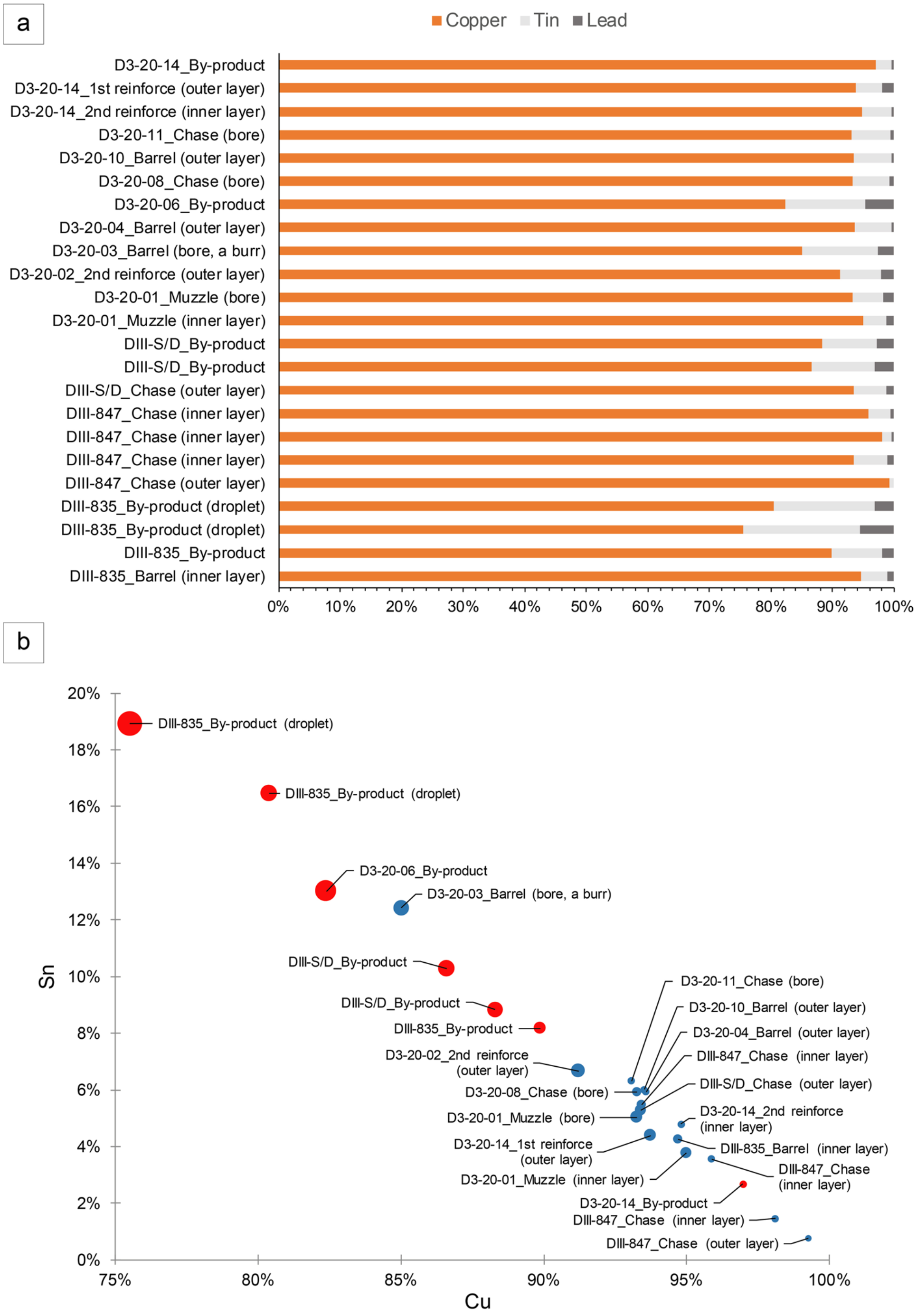
[6] The English and commented edition of this treatise by Smith and Gnuci (1990) is referenced here.

[7] Here is described the conventional procedure of seventeenth-century hollow casting. Experimental or uncommon methods were also proposed (e.g. Firrufino 1648:101–103), but their application was limited. Composite guns (iron-lead-copper) retrieved from the *Batavia* (1629) wreck site stand out (Green 1980). Local technical variations linked to operational and economic conditions should also be considered, as the Dutch and English non-standard bronze guns associated with the Portuguese galleon *Sacramento* (1668) attest to (Guilmartin 1982:134–138; Hoskins 2003:45–46). However, only a few other Dutch composite guns are known worldwide (Brinck 2020a:27).

[8] The desired physical qualities of clay and alternative acceptable compounds for making moulds are also mentioned by Biringuccio (Smith and Gnuci 1990:218–220).

[9] This upward position was the most effective to favour the material soundness at the gun's critical part, the breech, which was subjected to the greatest internal stresses (Guilmartin 1982:140; Murphy 2001:94).

Fig. 11 Mean composition of samples: **a** bar plot of the Cu-Sn–Pb content; and **b** comparison of Cu and Sn of the gun remains (blue) and casting by-products (red); differences in the Pb amount are indicated by the circles' diameter. Images: A. Zuccolotto



of tin would counterbalance the deficiency of this element in the last areas to solidify (inverse segregation) and improve the alloy's fluidity to avoid sponginess and porosity.[10] The heavy-weight torrent of molten metal was a significant stressor for the mould, therefore the pouring had to be done very carefully and an adequate filling of the feeding head was essential. The solidification process was developed at room temperature for several days, for such slow cooling conditions made it possible to obtain a relatively homogeneous material.

Breaking the mould, finishing, and proofing (step 4)

Once cooled, the mould was lifted, disassembled, and broken. Then, the core was extracted, the feeding head and any excess material from the gun sawn off, the vent or

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[10] According to Barker, this addition lowered the melting point of the alloy guaranteeing the function of the reservoir but would have not affected the composition of the actual casting (Barker 1982:71).

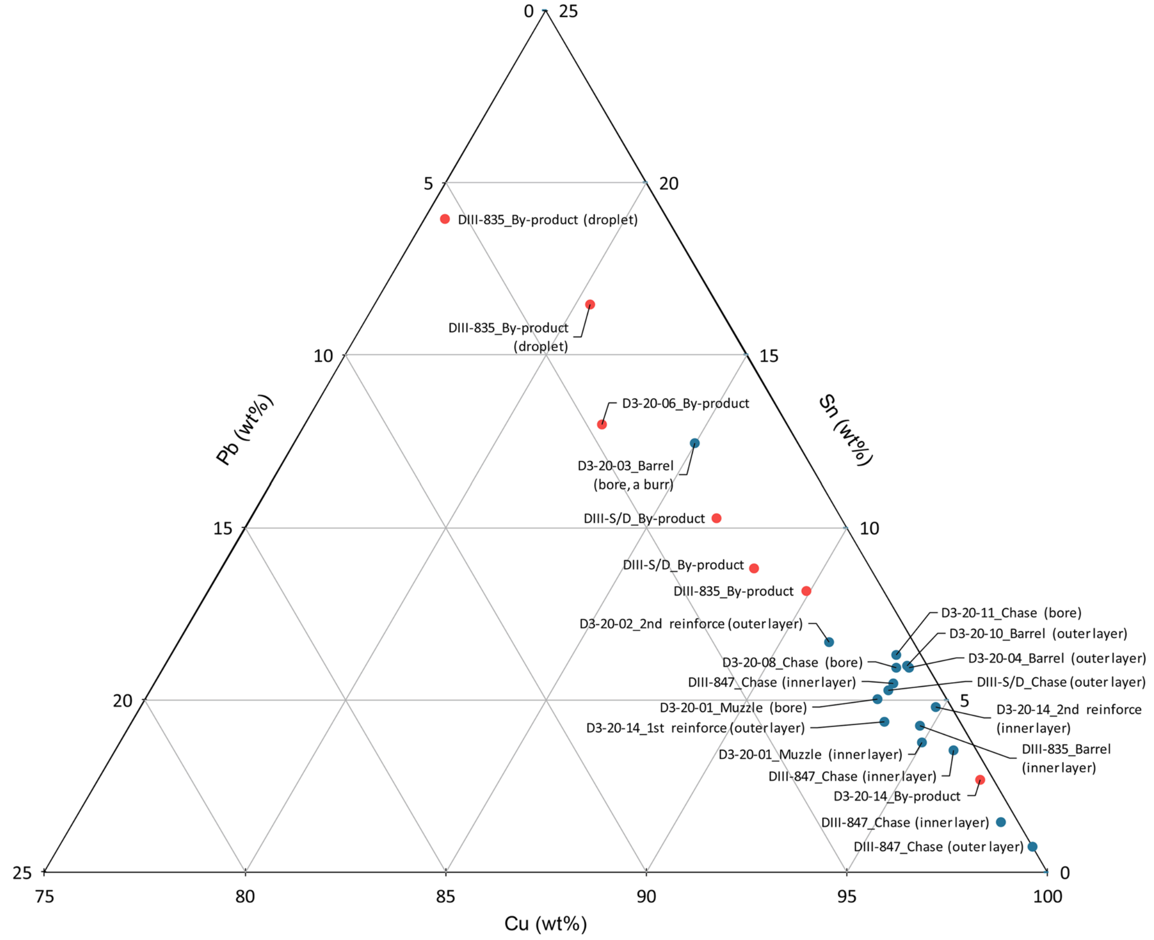

Fig. 12 Triangular plot of Cu, Sn, and Pb of the gun remains (blue) and casting by-products (red). Image: A. Zuccolotto

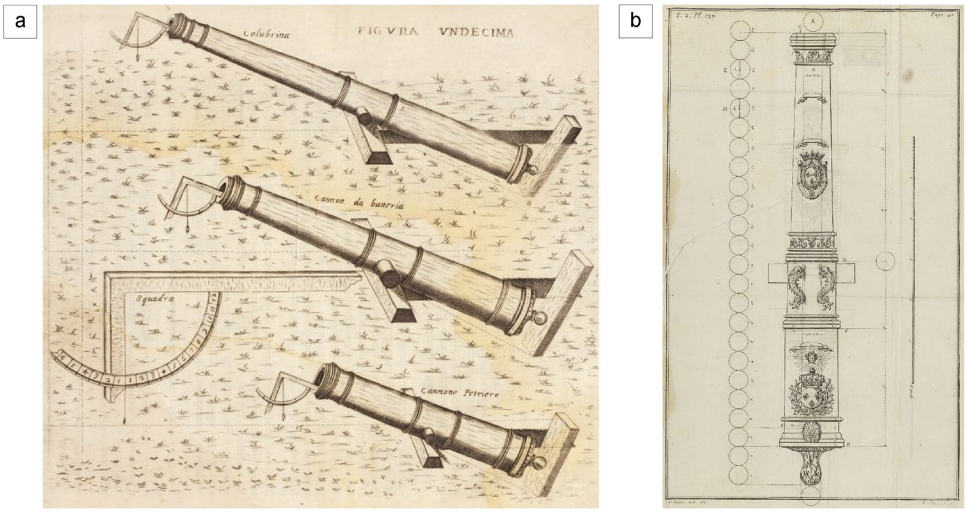

Fig. 13 Early-to-late bronze artillery: **a** a comparison between an early seventeenth-century culverin, cannon, and perrier, from Sardi's treatise *L'artiglieria* (1621, plate 11); and **b** a scale drawing of a French 24-pdr bronze gun from 1685, whose main dimensions are well established in proportion to its calibre (Saint-Remy 1707: plate 127; see also plate 147, where a 4 to 36-pdr guns series is depicted)

touchhole cleared or drilled, and the entire surface removed from imperfections. Given its implications for the gun's accuracy, the rectification of the bore was carried out to achieve a smooth surface. Moreover, the pieces underwent a strict quality assessment comprising a visual inspection and mechanical sound test to identify possible surface and

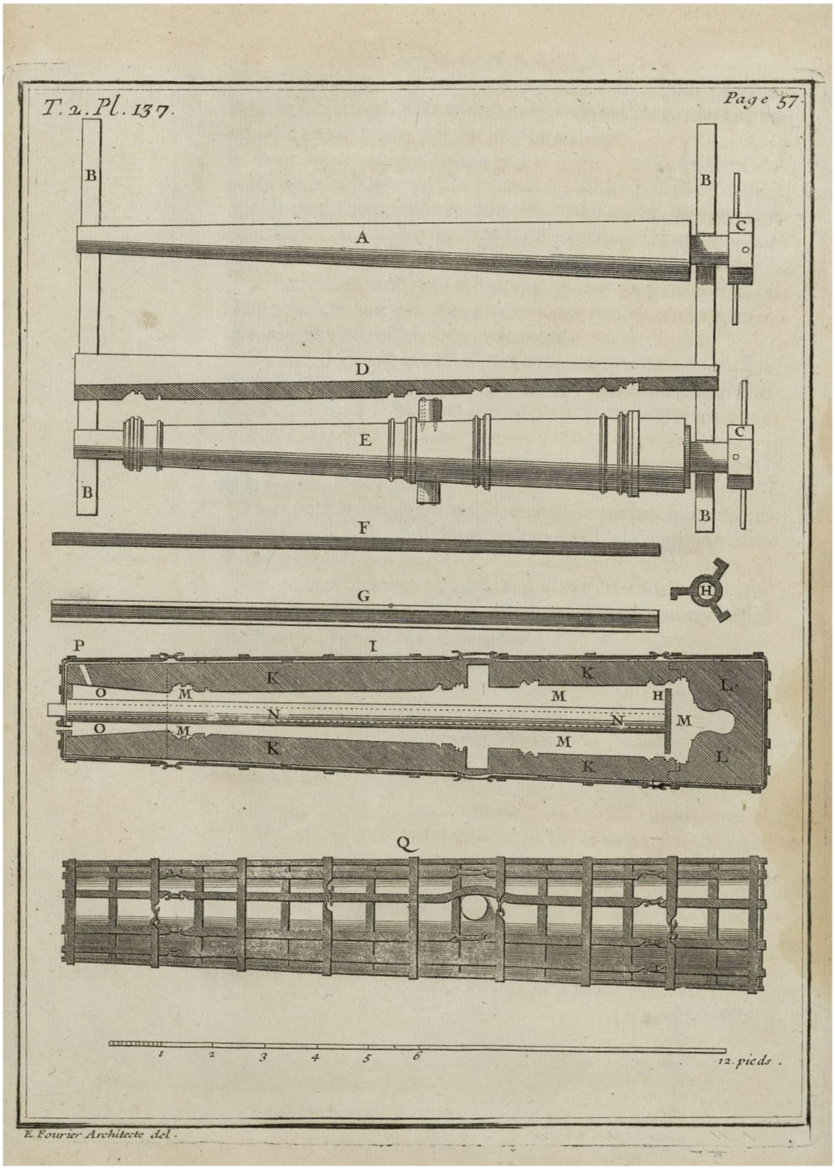

Fig. 14 Items involved in the mould preparation, including the wooden spindle (A), template or strickle board (D), the full-sized pattern of the barrel (E), the iron rod (F) for the core (G), the iron chaplet (H), and the finished clay mould of the barrel and breech-cascable: detailed inner view (I) and external appearance (Q); also note the feeding head above the muzzle (O) (Saint-Remy 1707: plate 137)

inner flows. For the gun to be accepted for service, a final proof firing was developed.

Minor and significant foundry defects or a complete failed casting might have been related to different interdependent factors during steps 1, 2, and 3. This situation, reflected by the remains recovered from the Delta III site, is further assessed in the next section.

On the casting defects and failed products

Gunfounding was a very complex practice. Obtaining a sound casting demanded a large expertise and rigorous control of several interrelated variables in every stage of the process. Errors were not unusual and their consequences on products covered from outer surface imperfections such as porosity to inner blowholes, cracks, and misruns (incomplete casting), among other defects. A gun's barrel was not equally stressed in its radius and circumference during firing (see Murphy 2001:73–75, for an analysis of stress distribution). Therefore, while the slight surface deficiencies were evident and non-catastrophic for the gun's performance, internal defects were imperceptible to the naked eye and could have made the product unsuitable for service or useless at all.[11] The situations were not homogeneous and the acceptance

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[11] Mechanical properties of bronze castings are also conditioned by other microstructural characteristics such as dendrite arm spacing, macro- and micro-segregation, morphology and distribution of inclusions, which in turn are conditioned by the casting technique (Taşliçukur et al. 2012).

Fig. 15 A depiction of two stages of the gunfounding process at the Woolwich arsenal, of about mid-to-late 1770s, from Jan Verbruggen's collection of foundry drawings: **a** the setting up of moulds; and **b** the pouring of molten metal. The authorship of these drawings is debated between Jan Verbruggen and Paul Sandby. Courtesy of the Semeijns de Vries van Doesburgh Foundation (https://janverbruggen.com/the-foundry-drawings-2/)

or rejection of a deficient piece depended much on the type and location of flaws, the quality standards and its destiny.[12]

The well-known major technical constraints in casting suitable large bronze objects were probably solved by the early fifteenth century (Guilmartin 2021). This empirical knowledge was closely linked to bell founding practice, further developed and later addressed in renowned metallurgical and artillery treatises.[13] Indeed, Biringuccio stated that accidents were not occasioned by fortune, but by human errors associated with misinformation, negligence, shortcuts, and savings during the process (Smith and Gnuci 1990:214–216). Based on this work and subsequent studies on gunfounding and naval ordnance (e.g. Sardi 1621:49–51; Barker 1983:70–71; Martin 1984:279–282; Murphy 2001:91–94; Hoskins 2003:29–51; López-Martín 2011:352–356) and metal casting technology (e.g. Campbell 2011; Sertucha and Lacaze 2022), a series of interrelated human and material failure factors and mid-term consequences and potential defects in products were summarized or inferred (Table 3).

Among studied bronze pieces from other sites (see above), minor defects on guns' surface were reported in a cannon from *La Belle* (1686) most likely cast at the Rochefort foundry between 1670 and 1679 (Keith et al. 1997:149) and the French guns recovered from the 90-gun warship HMS *Association* (1707), cast in 1638 and exhibiting blow holes and shrinkage sinks (Upton 1970, cited in Tylecote 1976:96).[14]

Guns severely damaged by a fire or a blast were also recorded in different contexts. Evidence of artefacts subjected to intense heat during the fire at the Grand Storehouse (Tower of London) in 1841 stands for the first case (Fig. 16a). The account of the salvaging of the 90-gun Danish ship HDMS *Dannebroge* (1710) is also intriguing. In 1711, twelve tons of fragmented bronze guns were recovered and melted down to re-cast smaller pieces. This debris seemed to result from the damage suffered when the vessel burnt and exploded (Christoffersen 1998:145). The inspection of three fragmented bronze pieces, two of them cast in 1604, from the VOC ship *Nassau* (1606) led authors to suggest that their condition could be the result of the heat suffered during the ship's burning (Bound et al. 1998:90–91, 101–102) (Fig. 16b). Another gun alleged to be subjected to firing was found isolated in an underwater context, near Fågelskär, in Stockholm's central archipelago and is nowadays hosted in the Swedish Army Museum (Armémuseum). It was cast in 1616 and displays the coat of arms of the Duke Johan of Östergötland (1606–1618), Sweden (Roth 2021) (Fig. 16c). Some details of the last two specimens also resemble those exhibited by failed castings (see above).

Scraps of bronze guns from the period were also found in inland archaeological sites, such as the remains of the Swedish castle of Kronoberg, ca. 1440 s to 1650 s (Smålands Museum – DigitalMuseum, pieces Nos. M

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[12] Some defects in ships' guns, such as a deviation in the bore alignment and inner gas voids shown by a *media-culebrina* (demi-culverin) recovered from *El Gran Grifon* (1588), could seriously affect their effectiveness in action, yet it passed for service (Martin 1984:284–285).

[13] This fruitful nexus between both industries remained for a while; to some extent, the production of bronze guns in continental Europe during the sixteenth century was still in charge of bell founders (Hoskins 2003:46–47). On the other hand, López Martin posed that bell founders made guns at an early stage, but once gunfounding was developed, it was more usual to find gunfounders casting bells and other items than vice versa (López Martin 2011:365–367).

[14] Defective and/or broken bronze guns have been also reported in several sixteenth-century shipwrecks (e.g. Martin 1972:63; Mihajlović et al. 2018:14–17). If this evidence stands for old pieces transported as cargo/ballast, guns exploded on board during firing or post-depositional processes, is an issue not easy to solve. In certain underwater contexts, mechanical and erosion conditions can also largely affect bronze guns (see van Duivenvoorde 2010).

Table 3 Common failure factors and undesirable functional and aesthetical defects associated with gunfounding, with emphasis on mould making and actual casting (melting, pouring, solidification, and cooling)

Failure factors	Mid-term consequences	Defects on the products
Employment of a low-quality (e.g. low refractoriness), non-uniform clay or earth for making the mould	Mould shrinks and cracks after drying or baking (most could be replastered)	Surface defects (e.g. veins/rat tails); mould partial break (due to pressure of molten metal); fusion (between the metal and the clay); and swell
Incomplete drying of moulds layers or partial baking of the finished mould	Surface coldness and moisture (that suddenly boiled once in contact with molten metal from the kiln)	Gas porosity (e.g. pinholes, blowholes, blisters); surface sponginess; incomplete casting; and mould harm
Deficient reinforcement of the mould or locking of mould parts' unions	Mould structural weakness	Mould break or collapse
Narrow or small vents	Insufficient room for gases to escape (i.e. poor venting)	Scares (shallow blows); and gas porosity
Improper cleaning of the mould's inner surface (e.g. residues of the model and holes)	Adhering molten metal to the mould's walls	Rough or irregular surface, coarse decoration
Asymmetrical mould or misalignment of the mould's parts (e.g. inaccurate siting of the chaplets)	Irregular axis; core deviation; incorrect assembling	Irregular gun's metal thickness (at the foot or head); off-centred or awry bore; shift or mismatch of the breech; and flash (fins/burrs)
Cracking of the core surface (e.g. because of low-quality clay)	Penetration of the molten bronze through the fissures	Non-smooth or irregular bore surface
Low-compression of the base and earth used to cover the well where the mould is placed	Weak foundation and external support; instability of the mould	Mould displacement, break, or collapse
Poor heating of the furnace; unsuitable managing of fusion times; inadequate alloy composition	Material not completely melted; low fluidity alloy poured into the mould	Sponginess; shrinkage porosity; misruns (incomplete casting); and cold shuts (round edge laps at the surface)
Excessive heating of the furnace	High pouring temperature of molten metal	Fusion; and rat tails and buckles
Insufficient charging material	Underpour (not enough feeding material to offset metal contraction during cooling)	Incomplete casting; and shrinkage porosity and outer cracks or depressions, especially at the muzzle
Not well-controlled pouring of the molten metal	Slow, interrupted, or excessive pouring rate; inadequate filling of the feeding head	Gas porosity; sponginess; cold shuts; and washes (due to erosion of the mould surface)
Uneven or uncontrolled chilling of the mould	Early cooling while pouring; different solidification rates in mould parts; residual (internal) stresses	Misruns; shrinkage porosity; hot tears (during solidification); cold tears (during solid state cooling); and warpage

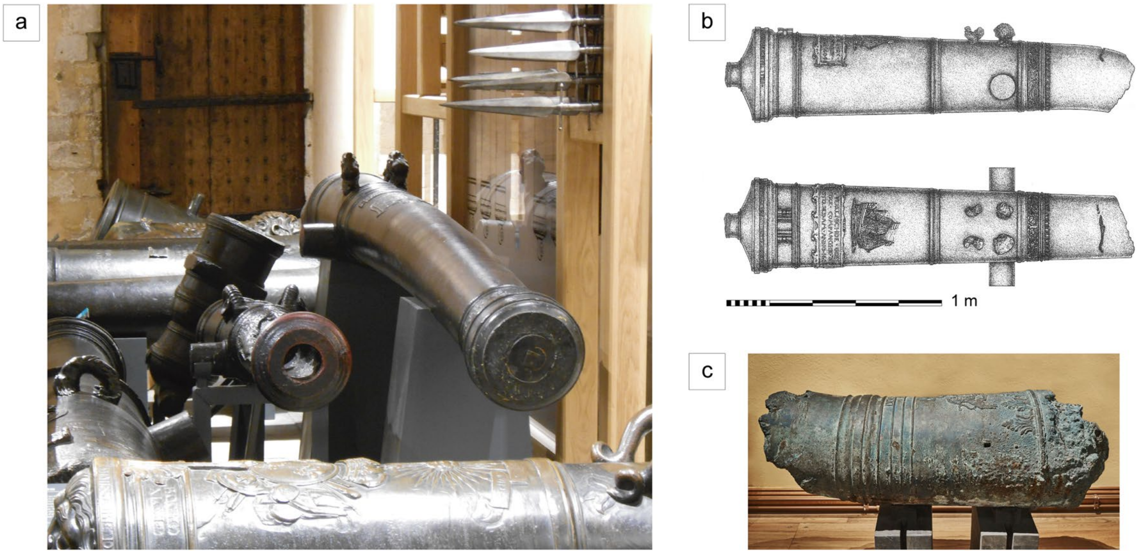

Fig. 16 **a** A ca. 1600 Spanish 12-pdr bronze demi-culverin whose chase was bent by fire, hosted at the Tower of London; **b** remains of one of the damaged bronze cannons recovered from the *Nassau* (1606); and **c** bronze gun recovered from an underwater site in Sweden. Images: a) NC Ciarlo (see also Blackmore 1976:146–147); **b** after Bound et al. (1998: Fig. 39); and **c** A Svedberg, © Armémuseum – DigitalMuseum (https://digitaltmuseum.se/0211810758646/hertig-johans-eldror; licence: CC BY)

17000–1953 and M 17000–174), a fragment of a Tudor falconet from the Parish of St Saviour, in Jersey, Channel Islands (Waterhouse 2013:91–92, Fig. 4), and a section of a barrel located near the fortress of the Mancera island, in Valdivia, Chile. This piece, most likely from the early-to-mid seventeenth century, shows part of the founder's name on its surface: …*A* | *TEXEDA*… for Alexo de Texeda, i.e. Alejo de Tejeda (Carabias Amor et al. 2023).

The occurrence of this fragmentary and scarce record is most likely related to the fact that bronze scrap was usually melted down to re-cast guns or other pieces such as statues and coins (see below). Most of the re-cast old bronze proceeded from obsolete pieces, damaged or exploded guns, and/or failed castings. Useless guns would be expected to be shipped in one piece and fragmented in the foundry before smelting. On the other hand, blast guns should show some evidence of the crack or fracture pattern from inside-out typical of blow-up pieces, most likely near the breech or first and second reinforces (e.g. McConnell 1988: Fig. 15). Pieces showing gunfire injuries, for instance by a direct hit, usually present localised damage (Brinck 2020a:85, Fig. 78).

Neither situation is reflected in the remains of the Delta III site. On the contrary, a series of casting imperfections associated with a failed production was recorded by a surface eye-naked examination and microstructural characterisation. These recorded defects were in form, discontinuity, and microstructure, as defined by Murphy (2001:89). While some degree of gas and shrinkage porosity can be considered typical of cast bronzes from the period, macroscopic and microscopic features attest to an unusually high level of imperfections. Given their extension, they resulted in catastrophic consequences for the final products, making them completely useless. Altogether, outer and inner flaws recorded in the analysed samples point in the same direction. Were these defective castings in the hands of the master founder or an apprentice? This is hard to assess. Regardless, the analysed assemblage indicates that the failed products were likely the result of a combination of factors across the casting process, related to human decisions, technical means, and raw materials.

On the quality of bronze alloys

According to Biringuccio, in the art of casting the proper and true alloying element for copper is fine tin. The bronze composition was determined by the kind of work (e.g. statues, bells, guns), which in turn relied on the judgment and experience of each founder (Smith and Gnuci 1990:210–211). Until the eighteenth century, there was no common agreement on the desirable composition for guns; the discretion of each founder prevailed, therefore no standard, uniform composition was obtained. Moreover, quality issues arising from applying diverse mixing criteria were not unusual (see Aguilar Escobar 2008:174–175, for the Spanish case).

By the time of Sardi, a bronze alloy of about 100 pounds of fine copper to 8–10 pounds of fine tin was considered optimal (Sardi 1621:47–48). Monge also acknowledged that the copper-tin proportion should not be above 10 to 1 to obtain the desirable properties (Monge 1793–1794:54).

In practice, the applied formulas for casting bronze guns were not homogeneous (see Duponchelle 1932:40; Aguilar Escobar 2008:175–178; Ringer et al. 2013:8; López-Martín 2011:276–277). Riederer assessed the copper-tin–lead ratios of guns from the Museum of Military History, at the Vienna Arsenal, discussing the most common ranges (88–93% copper, 7–11% tin, and 0–2% lead) and detrimental deviations (Riederer 1977:40). Other post-medieval European guns analysed by Gilmour and Northover (2003) show tin contents ranging mainly between 5 and 10%. Higher values of tin (up to 14%) were also reported (Browne 1960, cited in Tylecote 1976:96; Forshell 1984, cited in López-Martín 2011:278).

This variability is related to several non-exclusive factors such as differences in the founders' preferences, the non-standardised methods for mixing, the heterogeneity of raw materials, and the usual combination of fine metals and old bronze (see below). Moreover, differences can be observed between gun genres of a particular context (McConnell 1988:15). Likewise, a certain range in the concentration of the alloying elements within each piece is expected in sound bronze guns, given the material characteristics, production process, and gun's area—e.g. tin and lead tend to accumulate in the breech area, while the higher content of copper is distributed at the muzzle (Forshell 1992:125, 137). This inner heterogeneity was reported in small pieces to a lesser degree, in particular across their wall's thickness (e.g. Iddan et al. 2022:9, 12).

The bronze of guns often contained minor proportions of other metal elements such as lead, zinc, and also iron impurities. For instance, all five Dutch cannons recovered from the *Batavia* (1629) wreck site have substantial impurities which seemed to proceed from the refined copper and/or were accidentally introduced during casting (Samuels 1992:98, table 6). On the other hand, by an *ex professo* addition of lead or zinc, gunfounders sought to improve some mechanical and aesthetical properties of their products (Meide 2002:31). Those complex alloys were not free of inconveniences if not well proportioned, demanding further care during casting (Duponchelle 1932:41). For assessing the rough copper-tin ratio and impurities, the founders applied a qualitative test based on the colour and brittleness of a chip. In this regard, Firrufino stated that a reddish-blue short shiver stands for a leaded-bronze alloy, which was considered dangerous for guns (Firrufino 1648:111). This caution was likely grounded in the lower tensile strength and ductility of these bronzes. However, as lead adds pressure tightness and acts as a lubricant, in small quantities, it would have contributed to the gun's soundness and machinability (Tylecote 1976:96; Murphy 2001:76; Campbell 2011:310; Witzke 2023:5).[15] Lead present in reported European guns from the period is usually below 1%, and up to 2% (Riederer 1977:37–38; Gilmour and Northover 2003:4; Ringer et al. 2013:9).

Summing up, differences in alloy composition and the presence of impurities were not uncommon in bronze guns from the period. The heterogeneity degree in the elemental composition of barrel fragments from the Delta III site, however, may indicate either a deficient production, the application of a non-standard formula, the use of scrap material, and/or other irregularities during the casting process. It is worth mentioning the low tin content some pieces exhibited (e.g. gun No. DIII-847), which would have been inconvenient for its manufacture and use.

Melting down of old metal in bronze foundries for casting serviceable ordnance

Recycling could be broadly defined as the re-utilisation of certain manufactured goods, once used or considered scrap (e.g. a failed casting), as raw material to obtain a new product, similar or different to the original. This and other stages of the artefacts' life cycle or *chaîne opératoire* have been widely addressed through the study of archaeological remains (Thomas and Saussus 2020; Bray 2022; among others).

Melting down failed castings and old bronze pieces for re-casting new serviceable ordnance was a usual practice in England, Spain, and other European countries during the seventeenth century and thereafter (Wilson 1988:93; Aguilar Escobar 2008; among others). For instance, the picture provided by Lavery for the British vessels suggests that the use of old bronze to cast new guns was intensified by the hand of an increasing use of cast iron pieces to equip most but the largest ships (1st and 2nd rates) since about the 1750s (Lavery 1987:85–86).

Not only unserviceable guns were selected for this purpose, but also other pieces such as bells and statues (López-Martín 2011:279–280). As their copper-tin proportions were not within the usual range of gun alloys, gunfounders needed to adjust the proportions to obtain a suitable product. Pollard mentioned that church bells were melted down to cast cannons in Revolutionary France. Experiments carried out by chemists around 1790 allowed them to separate copper from the tin of bells, and estimate the content of copper recovered on quantitative grounds (Pollard 2013:339–340; see also Monge 1793–1794:54–58).[16] In the preceding century, to obtain the appropriate proportions for guns, this data was roughly estimated by bell- and gunfounders.

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[15] The addition of lead in higher quantities, even if it was prejudicial, was acknowledged as a formula to reduce the cost of guns (López-Martín 2011:357).

[16] Reciprocally, commemorative bells were cast with bronze guns taken as war trophies (Smith and Gnuci 1990:223). Also, scrap guns have been used to cast statues and other items (Roth 2021).

Fig. 17 A Renaissance view of the interior of a gun foundry: Pulvis Pyrius (Invention of Gunpowder), plate 3 from *Nova Reperta*, based on a design of Flemish artist Jan van der Straet, known as Johannes Stradanus (1523–1605), and later engraved by Philip Galle for the print series, ca. 1580–1605. Courtesy of the Smithsonian Libraries and Archives (ID: SIL-nouareperta00stra_0009, https://library.si.edu/image-gallery/110721)

A late sixteenth-century engraving depicting the interior of a foundry provides a snapshot of the various activities related to gunfounding. One, in particular, attests to the recycling of old bronze. In the background, through the middle arch, a man is melting down parts of broken guns which were hoarded in a pile near the furnace (Fig. 17).

This practice provides the most likely explanatory framework for the final destiny of bronze scrap recovered from the Delta III site. Moreover, the masses of amorphous bronze and barrel pieces welded together suggests that they could have even resulted from an early failed attempt to recast broken guns, which were only partially melted down. To melt down, some of the failed products carried on board the vessel should have been fragmented into smaller pieces. The size heterogeneity of the studied materials suggests that no specific criterion was followed before they were stowage, and at least part of the cargo was shipped in the as-cast condition.

Conclusion

This study allowed us to better understand the available knowledge and activities associated with gunfounding. It was a laborious, expensive, dangerous, and difficult art. In particular, macroscopic and microstructural data obtained from the scrap bronze remains retrieved from the Delta III site have provided new insights into the quality of the materials used and the factors involved in the failed castings.

The design, decoration, and marks of various gun fragments point to a two-fold possibility: at least part of the assemblage was most likely cast in the same foundry and linked to a renowned family of seventeenth-century German bell and gunfounders. Meant to be melted down and re-cast into new pieces, the scraps of bronze guns were left halfway resting in the bottom of the Bay of Cadiz. That the failed products were not meet the required quality to melt down at this workshop and/or it was more profitable to sell them as bronze scrap to foreign foundries, among other possibilities, should be further explored. Their final destination also deserves additional attention, given the well-known practice of recycling old bronze in foundries such as the Royal Artillery Factory of Seville.

Analysed evidence attests to the challenges and drawbacks that specialised founders usually faced at workshops of the time. Despite the large empirical knowledge and skills they had, reflected in the impressive products that survived up to nowadays, and the acknowledged importance of bronze guns for ships, armies, and states, the outcomes of this research support the idea that seventeenth-century bronze gunfounding was still far from being a standardised practice.

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Data availability Research data are available at the Underwater Archaeology Center of the Andalusian Historical Heritage Institute, and at the Department of Materials Science, Metallurgical Engineering and Inorganic Chemistry, Faculty of Marine and Environmental Sciences, University of Cadiz, in Cadiz, Spain. Further information not included in this article is attainable to the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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