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Exploiting the guns of the Santíssimo Sacramento*: an analysis of early modern naval ordnance, gunnery and gunfounding*

The following is a study of ordnance recovered from the wreck of the Portuguese ship *Santíssimo Sacramento*, sunk off Salvador, Brazil, in May of 1668. Its purpose is to exploit a unique collection of ordnance in order to improve our understanding of the theory and practice of naval gunnery and the casting of bronze ordnance during the early modern era, and to demonstrate in the process the utility of nautical archaeology as a window to the past.

A *galeão* and thus by definition a warship, *Santíssimo Sacramento* was at the time of her sinking the flagship of the annual convoy of the Companhia Geral do Comerçio do Brasil, the Portuguese Brazil Company, outbound from Lisbon. A famous tragedy in Portuguese history, the loss of *Santíssimo Sacramento* finds an English parallel in the loss of Henry VIII's flagship, the carrack *Mary Rose*, off Portsmouth in 1545 and a Swedish parallel in the loss of the galleon *Vasa*, sunk in Stockholm harbour in 1622. Although the Portuguese vessel is the least well known of the three, the parallels extend beyond legend and popular culture to the considerable historical value of physical artefacts recovered from the wrecks. Relevant to our concerns, the Portuguese vessel went down in much deeper water than the other two and in a more hostile environment. Whereas *Vasa*'s hull and much of its contents were preserved almost *in toto* by the cold, brackish, barnacle-free waters of the Baltic, and some three-quarters of *Mary Rose*'s hull and much of that which lay within were protected by an anaerobic blanket of silt, *Santíssimo Sacramento* was fully exposed to scouring currents and marine life, leaving little behind but the ballast pile – within which, to be sure, important artefacts were preserved – and the ship's ordnance, the subject of the following analysis.

For nearly three centuries the location of *Santíssimo Sacramento*'s wreck was lost to all but local fishermen to whom the site, notorious for snagging nets, was an underwater reef known as *o galeão*. The connection was not made until the mid-1970s, when sport divers discovered the wreck and began looting it. The first looted objects to attract public attention were bronze cannon sold to salvage yards as scrap. Providentially, the wreck lay within the jurisdiction of Brazil's 2nd Naval District, under the command of Vice Almirante Fernando Ernesto Carneiro Ribeiro, a serious student of naval history. Hearing reports of 'old cannon' in salvage yards, Carneiro investigated. Instead of the pieces of Napoleonic vintage he had expected, he found seven substantially older bronze pieces including several beautifully preserved English guns cast in the 1590s.[1] He immediately slapped a prohibited zone around the site and, with the endorsement of Capitão-de-Mar-e-Guerra (RRm) Max Justo Guedes, director of the Serviço de Documentação Geral da Marinha, the Historical Service of the Brazilian Navy, sought support for a recovery effort.

The recovery of *Sacramento*'s guns and their value

In response to their entreaties, the Navy assigned its sole submarine rescue vessel, *Gastão Moutinho*, commanded by Capitão-da-Fragata Oscar Moreira da Silva, and its complement of divers to *Santíssimo Sacramento* in a salvage archaeology operation. During 1976–78 *Gastão Moutinho*'s divers, working under the guidance of archaeologist Ulysses Pernambucano de Mello e Neto, recovered a host of artefacts including two bronze astrolabes and the signet ring of a senior Portuguese official that removed any doubt as to the identity of the wreck.[2] Of importance to the present study, they recovered 19 bronze cannon to which we can add the seven looted pieces impounded on Admiral Carneiro's authority under the provisions of Brazilian admiralty law. *Gastão Moutinho*'s divers also recovered eight cast-iron cannon before those in charge realised that they deteriorated catastrophically on exposure to atmospheric oxygen. These guns provided the data for the study that follows. The value of these guns stems in large measure from the fact that they form a coherent and largely complete collection of early modern naval ordnance of unimpeachable provenance: the actual gundeck of a known warship at an established date.

In dealing with early modern ordnance on public display and in museum collections we rarely know why a given piece survived. Was it preserved because it was unusually beautiful? Because it was too unwieldy to be taken into the field? Because of association with some long-forgotten event? In most cases we simply do not know. These questions are particularly vexing when dealing with bronze ordnance, since worn, damaged or obsolete bronze pieces were habitually melted down and recycled into newer guns, not only reducing the number of surviving pieces, but rendering the reasons for their preservation obscure in all but a handful of cases, mostly involving archaeological recovery from an underwater wreck, as is the case here.

The author's involvement with *Santíssimo Sacramento*'s guns began with an invitation from Capitão-de-Mar-e-Guerra Guedes to travel to Brazil in October of 1978 to study them. The initial findings of my investigation were published in *Navigator*, the journal of the Brazilian Navy's Historical Service, in 1981[3] and in *Technology and Culture* in 1983.[4] The present article originated in an October 2001 presentation at a conference on material culture hosted by the Smithsonian's National Museum of American History. It revisits the original data set with the benefit of knowledge gained during the intervening 20 years in materials science, internal ballistics and cannon founding, and in the history of the 1624–54 Luso-Dutch struggle for control of Brazil, for which *Santíssimo Sacramento* and her guns were designed and constructed.

Santíssimo Sacramento as a warship

Before addressing the guns in detail a few words on *Santíssimo Sacramento* and the environment for which she was designed are in order. One source states that she carried 60 guns,[5] a figure that is compatible with our expectations of a vessel intended to serve as flagship for convoys of the Companhia Geral do Comerçio do Brasil, laid down about 1649 and launched no earlier than 1650, probably in 1653. The absence of any guns bearing dates later than 1653 and the fact that the best of her heavy bronze ordnance was cast in that year (Table 1) militates against a later launch date. Inasmuch as the struggle for Brazil did not end until 1654, and unexpectedly at that – the Dutch simply abandoned their Brazilian interests under the pressure of the First Anglo-Dutch War of 1652–54[6] – it is clear that she was built for war. That the war in question was fought far from home in an age in which the most powerful warships were insufficiently seaworthy for transoceanic operations suggests that she was relatively large for her weight of ordnance by English standards. Those standards are relevant, since we know a great deal more about contemporary English warships than about their Portuguese equivalents. In brief, English third-rate warships, as distinct from the huge first- and second-rates built to dominate waters close to home, *could* engage in transoceanic operations, albeit with a reduced ordnance load.[7] It is thus reasonable to view *Sacramento* as a third-rate equivalent.

In this light it is useful to review the armament of contemporary English third-rates. The Royal Navy's Ordnance Establishment of 1666, a list of the armament of all English warships as of April of that year, yields four third-rate warships of 60 guns.[8] Their main batteries consisted of 22 or 24 32-pounders, that is guns firing a cast-iron ball of 32 pounds, mounted on the lower gundeck. Of the four vessels, one mounted 26 9-pound demi-culverins on the middle gundeck; the other three mounted 24 and 26 12-pounders respectively, plus two and four 18-pound culverins. The vessel with the lightest second-tier ordnance also carried ten sakers, nominally 5-pounders, almost certainly mounted on the upper deck.[9] The culverins, demi-culverins and sakers

Table 1 Bronze guns recovered from the *Santíssimo Sacramento*. The weight marks give the weight of the barrel in *quintaes* (hundredweights), *arrobels* (fourths of a hundredweight), and *arrateis* (Portuguese pounds)

Ball weight in pounds	Date cast	Founder's marks	Author's identification number	Weight marks	Weight in pounds	Weight of barrel per pound of ball	Maximum barrel thickness as function of bore diameter
26	1649	Matias Escartim[a,b]	10	+36-2-10+	3758	144.6	0.97
26	1649	Matias Escartim[a]	11	+36-1-16+	3739	143.8	0.96
26	1649	Matias Escartim[a]	12	+36-3-08+	3782	145.5	0.96
26	1649	Matias Escartim[a]	14	+36-1-00+	3723	143.2	0.96
26	1649	Matias Escartim[a]	15	+35-1-00+	3620	139.2	0.95
26	1649	Matias Escartim[a]	16	+36-2-04/+	3752	144.3	0.96
28	Mid-1600s	A.G.F.[a,c]	9	39-1-16	4047	144.5	0.95
24	Mid-1600s	[a]	17	-37-0-8-	3808	158.7	0.96
11	Reign of João III	[a]	18	+25-1-08+	2601	236.5	1.06
11	Reign of João III	[a]	19	+25-3-08+	2657	241.6	1.07
11	Early 1600s	A.G.F.[a,c]	3	23-2-16	2430	220.9	1.06
11	Mid-1600s	[a]	4	25-2-0	2619	238.1	1.20
11	Mid-1600s	[a]	5	+26~0~1+	2671	242.5	1.04
11	Mid-1600s	[a]	23	+25~3~1+	2645	240.5	1.11
14	Mid-1600s	PDB[a,d]	6	31-2-12	3247	231.9	1.11
20	1590	John and Richard Philips	13	3640Ã[e] 3600-1-6	3728	186.4	1.11
20	1590	John and Richard Philips	8	3610Ã[e] 3500-1-1	3620	181.0	1.14
20	1590	George Elkine	20	2700Ã[e] 2600-1-5	2702	245.6	1.14
20	1590	George Elkine	2	2650Ã[e] 2500-3-9	2654	241.2	1.16
11	Mid-1500s?	[a]	1	2630Ã[e] 2500-1-25	2619	238.1	0.95
8	Mid-1500s?	[a]	21	2640Ã[e] 2500-2-18	2637	329.6	1.12
20	1649	Conrad Wagwaert	7	37-1-19	3844	191.7	1.07
14	1622	Henricus Meus	22		3548[f]	247	1.09
20	1634	Assuerus Koster	24	38-0	3902	195.1	0.96
4½	Mid-1600s	Assuerus Koster	34	...	...	...	0.79
4½	1646	Henricus Vesterinck	35	...	...	...	0.62

a Indicates Portuguese royal crest on barrel.

b In my previous work, I conflated Matias Escartim's name with that of Lieutenant General of Ordnance Rui Corea Lucas, whose name was cast on the barrels along with Escartim's, making the latter Lucas Matias Escartim. I am indebted to Dr Luis Filipe Marques de Sousa, formerly of the Museu Militar, Lisbon, for correcting me on this point and for identifying the founder PDB.

c A.G.F. for Antonio Gômes Feio, a Lisbon-based founder.

d For Pedro Dias Bocarro, a Goa-based founder.

e Indicates weight in pounds avoirdupois.

f Based on the gun's calculated volume, as explained in Figure 8.

were mostly if not entirely cast-bronze pieces of obsolescent design, the rest cast-iron ordnance of recent manufacture. As we will see, the weight, amount and pattern of armament provide both revealing contrasts and useful clues in evaluating *Santíssimo Sacramento*'s armament.

The capabilities, limitations and manufacture of early modern ship-borne ordnance

Our next step is to address the capabilities, limitations and manufacture of ship-borne ordnance in *Sacramento*'s day, an area in which there is a great deal of misinformation in general histories, much of it stemming from the implicit assumption that early modern ordnance can be judged by the standards of present-day artillery. In fact, modern rifled artillery firing high-explosive shells with smokeless, nitrocellulose-based propellants differs fundamentally in ballistic properties and tactical characteristics from early modern smoothbore ordnance using black powder to fire an inert spherical projectile. With modern artillery, long-range accuracy is both attainable and, because of the destructive power of high-explosive shells, tactically relevant. Long barrels are necessary to obtain long ranges. In contrast, early modern smoothbores were inherently inaccurate. This was due in the first instance to the space, or windage, left between the ball and bore to prevent the ball from jamming as powder residue built up with repeated firings. In consequence, the ball would rebound back and forth, or ballot, on firing, departing the muzzle in an unpredictable direction. It was due in the second instance to the inherent inaccuracy of a slowly spinning spherical projectile. Whatever spin the ball acquired from contact with the barrel was around an axis at right angles to the line of flight, causing the ball to hook or slice like a golf ball. More fundamentally, air flows in an erratic fashion around a slowly spinning sphere, causing it to deviate unpredictably from its line of flight in the manner of a baseball pitcher's knuckle ball. The resultant inaccuracy was multiplied by the fact that the barrels were mounted rigidly in wooden carriages that moved rearward with recoil on firing, transferring their lateral and vertical movement to the projectile. The net result was that gunners could not reliably hit small targets at long ranges and the maximum effective range of naval guns was of the order of 200–300 yards, a figure further reduced by the difficulties of aiming from a rolling deck. Finally, the destructive capabilities of inert projectiles fell off sharply as range increased. On occasion, a long shot would cripple the rigging of a pursuing enemy or disable a fleeing foe, but the expression 'long shot' says it all.

The next misconception involves the relationship between barrel length and maximum range. For the reasons indicated, maximum range was of peripheral tactical relevance in early modern warfare at sea. That notwithstanding, the notion that maximum range was important and that it was proportional to barrel length has enjoyed remarkable longevity. With modern artillery, maximum range *is* proportional to barrel length. This is for two reasons. First, the burning rates of nitrocellulose-based propellants increase as a function of temperature and pressure: the hotter the chamber and the greater the pressure the faster they burn. Second, the decomposition products are light, being entirely gaseous except for traces of water vapour. With proper powder grain geometry, the burning rate of the charge will increase progressively as the projectile moves down the bore, imparting increased velocity more or less indefinitely.[10]

The ballistic properties of black powder and their implications

None of the above characteristics applies to black powder, the traditional mixture of saltpetre, charcoal and sulphur in the approximate proportions of 75:15:10 by weight. Because of the thermochemical properties of black powder, the burning rate does not vary as a function of pressure or temperature. In addition, the decomposition products are relatively massive, consisting of 57 per cent solid particles by weight. These characteristics placed a strict upper limit on the velocity that a black-powder charge could impart and an equally strict limit on useful barrel length.[11] In practical terms, once a cannon ball had travelled 8–10 feet from the face of the powder charge it was moving as fast as ordinary grained black powder could move it. From the ballistic point of view, any additional barrel length was a waste of metal.[12]

But while barrel length had no appreciable effect on maximum range, it did have important structural consequences. That was because cannon were cast muzzle-up, and the greater pressure of molten metal at the breech resulted in denser and stronger metal where it was most needed.[13] We know that early modern gunfounders were empirically aware of the relationship because we can observe gradual but systematic reductions in barrel length and wall thickness over time. Gun metal, ideally an alloy of 9 parts copper and 1 part tin by weight, was expensive and the founder used no more than he had to. Moreover, shorter, thinner guns were lighter and easier to handle. With this in mind, the gradual reduction in length and barrel thickness in guns cast within the same national tradition – a phenomenon clearly observable in *Santíssimo Sacramento*'s bronze guns – reflects both gradual improvements in founding technique and a clear appreciation of just how short and thin guns could be cast at a given time.[14] Quality was ensured by proof firing with a heavier than normal projectile, a larger than normal powder charge, or both. Enough guns 'failed proof', that is, burst on firing, to give founders an accurate sense of how close to the limits of safety they were. Our best evidence is from the eighteenth century, but the technology of bronze cannon founding remained essentially unchanged from late medieval times through the early modern era, and proof firing was central to the process.[15]

Bronze cannon founders' methods and the importance of cast-iron ordnance

To appreciate fully what *Santíssimo Sacramento*'s guns have to tell us, it is necessary to go into the founding process in some detail. It started with the creation of a positive image of the gun, begun by wrapping rope around a wooden mandrel and finishing with wax. The positive was suspended above a long box, using the mandrel as an axle, and the final form was imparted by a strickle-board, a wooden template cut to the outline of the barrel that was pressed against the wax-covered positive which was slowly turned to impart the desired shape. As we shall see, this seemingly crude process could be remarkably precise. The trunnions in which the finished gun would be suspended in its carriage, lifting lugs or dolphins, royal crests, founder's marks and other external decorations were then sculpted in wax and attached to the positive.

The positive was then coated with successive thin coats of fine pottery clay to which an admixture of finely chopped wool and horse manure had been added. The first layers were dried in the open air, then, after an appreciable thickness had built up, a slow charcoal fire was lit in the box to harden successive layers of coarser clay. Once the mould had reached the desired thickness, it was reinforced with wrought-iron staves around which white-hot, wrought-iron hoops were shrunk. The mandrel and rope were then removed and the inside of the mould fired to melt out the wax, vitrify the clay and burn out the fragments of wool and horse manure, leaving a sintered surface to provide an escape route for the moisture released from silicates in the clay upon contact with molten bronze. The mould for the cascabel, the breech cap, was constructed by the same basic process.

Once the mould was dry, it was suspended breech down over a pit at the bottom of which the breech cap was firmly embedded in rammed earth. The core that would form the gun's bore was carefully lowered into the mould and centred at the base by means of a wrought-iron chaplet or *cruzeta* (Figure 1). This was critical, since a gun with an off-centre bore was inherently dangerous. The work in the pit was done by candlelight and, considering the fragility of the mould and the close tolerances involved, the standards of craftsmanship were remarkable. After the core was centred, the mould was lowered onto the breech cap and a feeding head or casting bell attached atop the mould. The whole assembly was embedded in rammed earth and channels cut to convey the molten metal from the melting furnace to the mould.

After the metal had been poured, the gun was left to cool – a critical part of the process that determined the crystalline structure upon which the metal's strength depended – then dug from the pit, broken out of the mould, and the metal from the feeding head sawed off. Finally, in most casting traditions the gun was weighed and the weight incised into the metal.

A final technical note is necessary before we turn to *Sacramento* and her guns. It involves the relationship between bronze cannon and cannon of cast iron. The ability to cast reasonably safe cannon of iron, first mastered by the English in the 1540s and then by the Dutch, Germans and Swedes, was an achievement of immense importance, but primarily for economic reasons. Iron guns were substantially larger and heavier than guns of bronze cast to fire a ball of the same weight. Worse, they were subject to internal corrosion and, partly as a result, were less safe. When they burst, they did not remain essentially intact as bronze guns did, parting like a torn sponge along a longitudinal line near the breech; rather, they blew apart in jagged fragments like a bomb. The primary drawback of bronze ordnance was its high cost. While we do not know what *Sacramento*'s guns cost, commodity prices give an idea of the difference between bronze and iron: in 1570, bronze cost £40–60 per ton in England, 3⅓ to 6 times more than iron; by 1670, bronze cost £150 per ton and the ratio had increased to 8⅓ to 1.[16] By *Sacramento*'s day, the British Royal Navy was armed mostly with cast-iron guns, and those that passed proof were acceptably safe, but British third-rates were armed primarily to fight close to home, and for a warship intended for operations in distant waters the weight advantages of bronze would have been compelling.

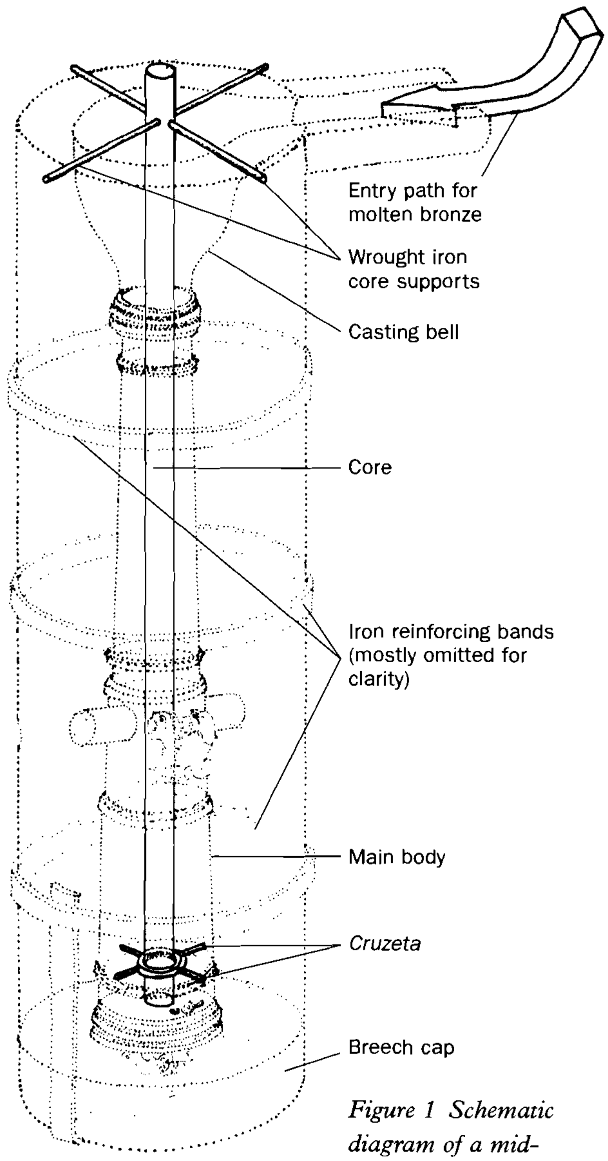
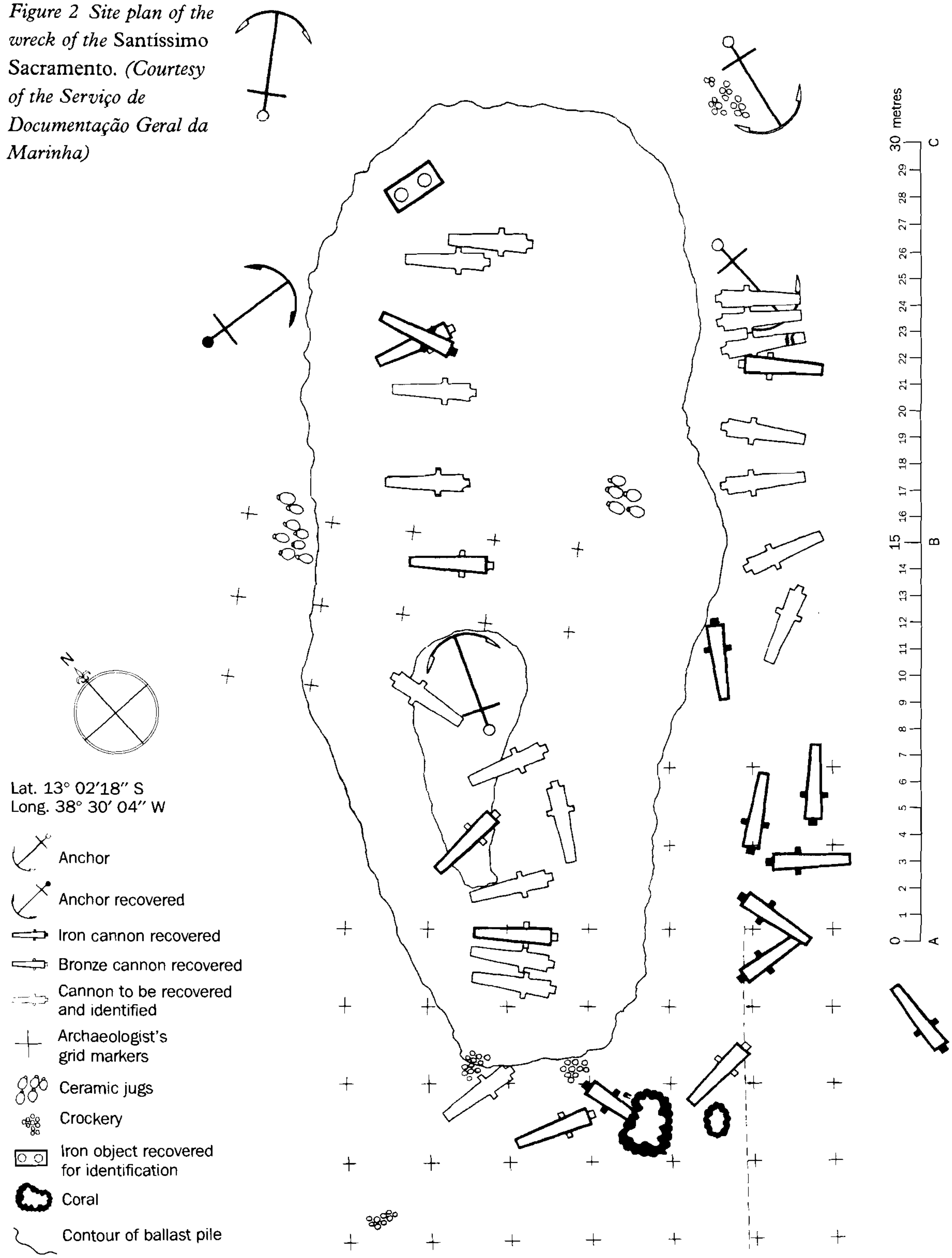


Figure 1 Schematic diagram of a mid-seventeenth-century Portuguese cannon mould. The cannon depicted is a Matias Escartim 26-pounder, number 12 in Table 1. The mould reconstruction is the author's, based on literary evidence extrapolating backward from later practice presented in de Beer, C (ed.), note 15. (John F Guilmartin, Jr)

Sacramento's guns: distribution and description

Thirty-four cannon, 26 of bronze and 8 of cast iron, were raised from the wreck; Table 1 lists the bronze guns and their salient features. In addition, we must take into account the 8 iron guns left on the bottom, adding to a total of 42 guns. For reasons addressed below, all but two of these were probably mounted on *Sacramento*'s enclosed gundecks. The archaeologist's site plan (Figure 2) shows the distribution on the bottom of most of the major items recovered, including 35 of the cannon. Though incomplete – the locations of the 7 cannon recovered before archaeological controls were imposed

Figure 2 Site plan of the wreck of the Santíssimo Sacramento. *(Courtesy of the Serviço de Documentação Geral da Marinha)*



are unknown – the evidence provided by the plan is critical to reconstructing *Sacramento*'s gundecks.

The distribution of wreckage suggests that the ship came to rest on the bottom, right side up on a relatively even keel. This disposition is plain from the arrangement of anchors and guns. The cannon were found in two ragged parallel lines flanked by four of the five anchors at what we can safely assume was the forward end of the ship, since a ship's main anchors were carried outboard in the bows. Deviations from this overall scheme are minor and reinforce the conclusion that the locations from which the cannon were recovered correspond closely to their locations on a horizontal plan of the ship before she went down.

The lines of cannon curve inward at the extreme stern just enough to suggest that the two cannon in the opposing lines closest to one another were stern chasers, mounted side by side to fire rearward on either side of the rudder. The lines of cannon are least regular at the stern, where the hull and superstructure would have been deeper, leaving a greater mass of rotting timber to disorder the rows of cannon in their slow trip to the bottom. The length of the lines of cannon suggests a gundeck about 158 feet (49 m) long and an overall hull length of about 200 feet (61 m) from stem to stern. *Sacramento* was thus, as we would expect, somewhat larger than contemporary British third-rates, whose gundecks ranged from 130 to 151 feet.[17]

Of the 26 bronze cannon recovered, two are very small pieces, 4½ pounders (Figure 6) that would have been mounted on the upper decks. In light of their beauty and small size they are surely representative of a number of similar pieces looted from the site, conceivably the 18 needed to fill out *Sacramento*'s complement of 60 guns. The rest of the bronze pieces are split almost evenly between 20-pounders or larger (12) and 12-pounders or smaller (10). This and the close spacing of the guns in their two rows erase whatever doubt we may have that the ship's main battery was mounted on two decks.

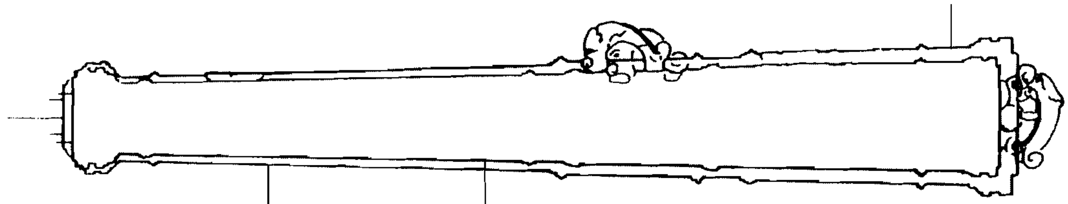
The eight iron guns recovered fell into two distinct categories. Judging by their gross external dimensions, four were 20-pounders or larger and four were 12-pounders or smaller, an observation that supports the two-gundeck hypothesis, since the plan indicates that at least seven of the eight were found adjacent to one another in an area corresponding to the starboard quarter; in other words, it would appear that the smaller guns of the middle gundeck fell through the rotting hull onto a like number of larger guns below them. *Gastão Moutinho*'s captain, Capitão-da-Fragata Moreira da Silva, formed the opinion, based on his divers' reports, that most if not all of the eight cannon left on the bottom fell into the 20-pounder or larger category. Logic suggests that *Sacramento* carried 22 guns on her lower deck, all 24-pounders or larger, and 18 guns on her middle deck, eight of them 20-pounders and ten 11-pounders (including the archaic English

8-pounder on the basis of size). The heavy concentration of guns at the stern of the wreck (Figure 2) suggests that two guns were carried there in chase, and the logical candidates are the two bronze 14-pounders. *Sacramento* would have looked very much like the Spanish galleon of 60–64 guns drawn by the Dutch master William Van de Velde the Younger in 1666 (Figure 3).

Turning to the ordnance, I have given the weights of the guns in the original Portuguese units. My purpose is comparative and, so long as I am consistent, Portuguese *arrateis* will serve as well as any other unit. In contrast, I have given the 'ratings' of the cannon, that is the weight of ball they were intended to fire, in pounds avoirdupois to facilitate comparison with the armament of contemporary ships of other nations. Since the weights of the guns and their projectiles are central to my analysis, my reliance on the weight markings incised on the guns' breeches requires explanation. Doubt as to the meaning of the markings was eliminated by calculating the volumes of selected cannon and determining their expected weights based on the density of bronze. While the results were imprecise in light of the complexity of the guns' shapes and variations in the density of bronze, they yielded a range of weights that encompassed those marked on the guns.

Figure 3 Drawing of a Spanish two-decker by William Van de Velde the Younger, 1666. It was pierced for 60–64 guns and must have been similar to Santissimo Sacramento *in appearance, although somewhat larger. A contemporary English warship of the same dimensions would have carried 70–80 guns.*[18] *(© National Maritime Museum, London)*

My confidence in the markings' accuracy is based on analysis of the double sets of markings on *Sacramento*'s six English guns, giving the weights of the pieces in question in English pounds avoirdupois and Portuguese *arrateis*. A least-squares regression analysis of the two sets of markings showed that they are parallel expressions of the same quantities in different, but consistent, units of measure with a correlation of 0.9989.[19] This analysis also yielded a value



Comparative data

Gun	Weight of barrel per pound of ball	Relative length of barrel	Thickness of barrel wall at base of bore
28-pounder	137 pounds	18.4 calibres	0.95 bore diameter
11-pounder	209 pounds	24.8 calibres	1.06 bore diameter

Figure 4 Comparison of a 28-pounder and an 11-pounder made by Antonio Gômes Feio. The outlines are drawn with superimposed centrelines and touchholes so as to depict the bases of the bores in the same transverse plane. (John F Guilmartin, Jr)

for the *arratel* of 1.027 pounds avoirdupois, heavier than the value of 1.012 pounds usually given.[20] Small discrepancies between the English and Portuguese weights of individual cannon make it clear that the Portuguese did not simply multiply the English weights by a conversion factor: they actually weighed the guns. They did so, moreover, with impressive accuracy: within 0.07 per cent on average and within 0.02 per cent if we throw out cannon number 13 as an outlier.[21] These findings indicate that English gunfounders and Portuguese arsenal workers observed similarly high standards of precision, suggesting a shared technical tradition.

Analysis of the guns recovered suggests that the *Sacramento*'s preferred main gundeck battery would have been of bronze 26-pounders, but that a shortage of first-class ordnance led to the inclusion of older bronze pieces of disparate calibres and numbers of cast-iron cannon. This hypothesis is supported by examination of the bronze Portuguese guns that we can unequivocally assign to the lower gundeck based on size. There are eight of these: a 28-pounder by the founder A.G.F. (Antonio Gômes Feio), the largest cannon recovered (Figure 4); a 24-pounder by an unknown founder (though unsigned, the piece is plainly Portuguese); and six 26-pounders by the founder Matias Escartim (Figure 5). The uniformity of these six guns suggests that their founder and his customers believed them to be of a superior design, an impression reinforced by analysis of their weight and their similarity to the earlier A.G.F. piece. Comparison with *Sacramento*'s captured Dutch guns (Figure 6) indicates that they were right. Though the three larger Dutch guns all fired a smaller ball – 20, 20 and 15 pounds respectively – they are heavier, longer, or both, than the Portuguese 26-pounders.

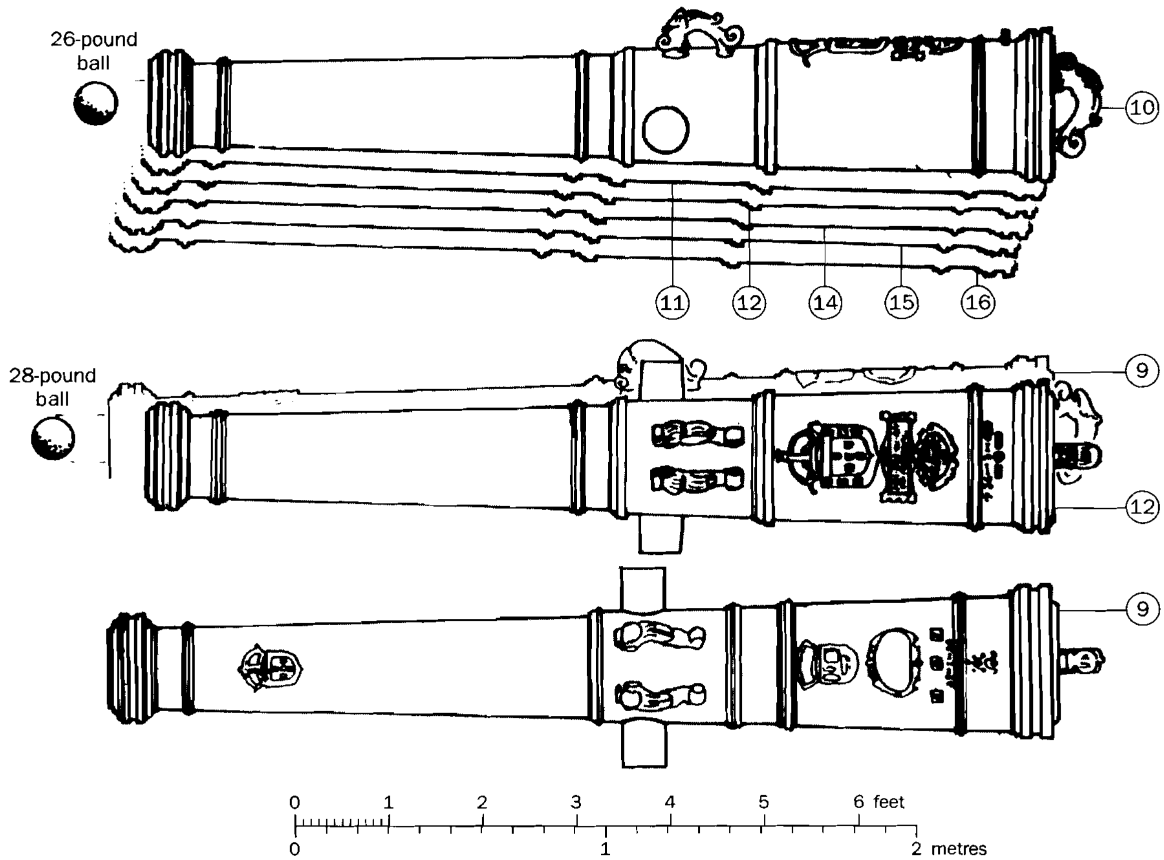


Figure 5 Six 26-pound cannon made by Matias Escartim and an Antonio Gômes Feio 28-pounder. Both Matias Escartim and Antonio Gômes Feio worked in Lisbon. (John F Guilmartin, Jr)

Sacramento's guns: the logic of size and efficiency

At this point we need to address the logic that dictated the size of the guns on *Sacramento*'s gundecks, bearing in mind that 11-pounders seem to have been preferred for her middle deck. In this we are assisted by the serendipitous fact that *Sacramento*'s largest recovered gun and one of her 11-pounders were cast by the same founder, Antonio Gômes Feio, permitting a closer comparison between the two categories of gun than would otherwise be the case.

The similarity in the lengths of 24- to 28-pounders on the one hand and 11-pounders on the other, graphically demonstrated here, was driven by the ballistic properties of black powder. If we assume a powder charge with a density of 58 lb/in^3 weighing three-quarters the weight of the ball, then the 28-pounder's charge would have occupied about 1.7 times the internal diameter of the bore, that is 1.7 calibres, and the ball would have travelled just over 8½ feet before exiting the muzzle, very close to our posited optimum length.[22] The 11-pounder's ball would have travelled a bit further, perhaps indicative of the founder's implicit awareness of the lesser ballistic efficiency of smaller bores. The principal difference between the two categories of gun is

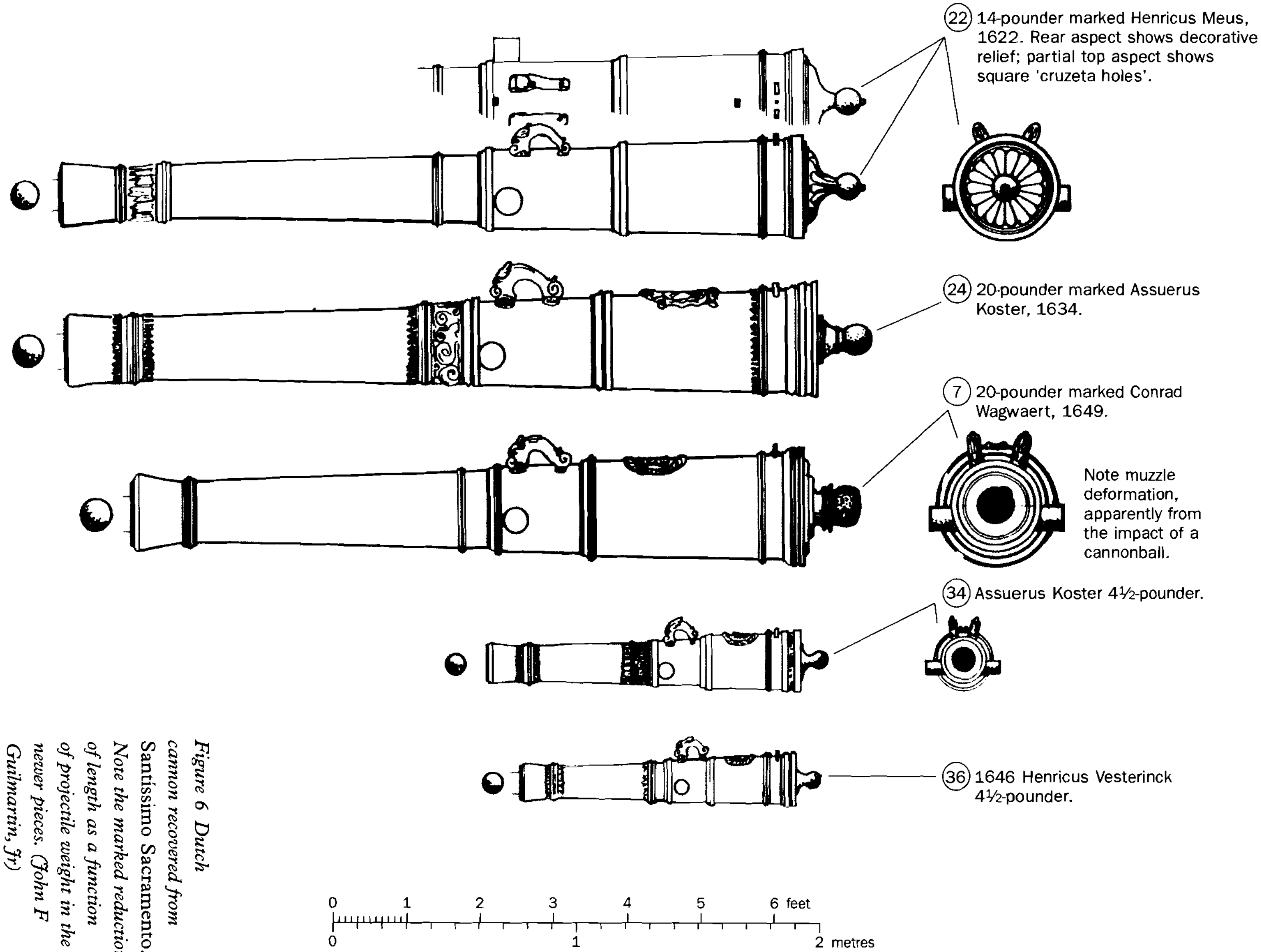


Figure 6 Dutch cannon recovered from Santissimo Sacramento. *Note the marked reduction of length as a function of projectile weight in the newer pieces. (John F Guilmartin, Jr)*

their relative efficiency. Significantly, the smaller cannon were heavier in terms of projectile weight than larger ones across the board, and the difference was not trivial. *Sacramento*'s six 11-pounders range from some 221 pounds of barrel per pound of ball (the A.G.F. piece) to over 242 pounds, all containing nearly 100 more pounds of metal per pound of ball than her 28- and 26-pounders.

It is legitimate to ask why these inefficient smaller guns were cast at all. In land service, the rationale for greater numbers of smaller guns, as opposed to a few larger ones, however ballistically efficient, is clear. The fixed restrictions of horse traction placed inflexible limits on the mobility of large guns, and several small projectiles were tactically more effective than a single large one when engaging dispersed human and animal targets. But at sea, where the criterion for success was the ability to inflict damage on an enemy ship, the advantages of larger guns in terms of ballistic efficiency and relative cheapness would seem to have been compelling.

In reality the issues were more complex, revolving around such questions as the strength and weight of decks, frames and bulwarks, centres of gravity and moments of inertia – though these were not explicitly understood for many decades. The naval architects who designed and built *Santíssimo Sacramento* undoubtedly had clear ideas concerning the preferred size, composition and arrangement of her lower and middle batteries. It is likely, therefore, that 26-pounders below and 11-pounders above represented a ballistic and structural ideal, the optimum combination of usable firepower that could be built into a large transoceanic warship in Lisbon – or anywhere else – in the 1640s and 1650s. Does *Sacramento*'s varied assortment of 15- and 20-pounders (of which there were no fewer than six, all of them, except for a single long, heavy and probably old Portuguese 15-pounder, either Dutch or English) therefore represent convergence toward the ideal or the acceptance of limited supply? The absence of first-class Portuguese cannon in the 15–20-pound category strongly suggests the latter, but we simply do not know.

Turning to what we can presume to have been the best pieces of *Sacramento*'s main battery, the barrels of the six Matias Escartim pieces were identical within the limits of my ability to measure them with a steel tape. Other less critical dimensions were not so closely controlled: the trunnions of two of the six are noticeably skewed in the horizontal plane. Comparison with Antonio Gômes Feio's 28-pounder suggests that the two founders were of comparable ability: the larger A.G.F. piece contains just over 140 pounds of bronze for each pound of ball thrown, while the Matias Escartim pieces contain from 140 pounds to just under 142 pounds. The Matias Escartim pieces' uniformity in weight is both remarkable and significant. The heaviest of the six weighed only 1.42 per cent more than their mean weight of 3740 *arrateis,* and the lightest only 2.93 per cent less, this despite the documented difficulty in controlling the density of cast bronze, a problem that was never solved as long as bronze cannon were cast.[23]

Sacramento's Dutch ordnance and the Luso-English founding tradition

Examination of *Sacramento*'s Dutch guns indicates that Dutch founding technology differed significantly from Portuguese and English practice. The considerable variation in colour among the Dutch pieces – when I examined them in 1978 the Conrad Wagwaert 20-pounder had a blackish, almost ebony-like sheen, and the Henricus Meus 15-pounder had oxidised to a light pastel green – suggests that Dutch founders had not established the same degree of control over their alloy as their English and Portuguese contemporaries. Examination of the Dutch guns also supports the proposition that over time founders within a given national tradition systematically reduced the length and weight of their guns as a function of projectile weight. The Dutch cannon were cast without weight markings, yet the two largest have Portuguese markings roughly incised on their barrels, suggesting that they were weighed in the field rather than in a fully equipped arsenal (Table 1). These Dutch guns were considerably less efficient than their Portuguese equivalents: the Assuerus Koster 20-pounder contains 195 pounds for each pound of ball and the Conrad Wagwaert 20-pounder 192 pounds.

Dutch foundry technique differed sharply from contemporary Luso-English practice in at least one demonstrable particular. Following a tradition that can be traced back to Biringuccio's *Pirotechnia* of the 1530s, the bores of *Sacramento*'s Portuguese cannon and newer English cannon were centred with a chaplet or *cruzeta* of wrought iron affixed to the base of the mould's core, as depicted in Figure 1.[24] The *cruzeta*, commonly a ring around the core supported by four arms, remained embedded in the gun. Where it had corroded away – surprisingly few had, particularly on Portuguese and English guns – I could surmise *cruzeta* design from the holes left behind. Where the *cruzeta* remained intact, I could locate the tips with a magnet.

The newer Portuguese and English guns showed holes or indications of ferromagnetic metal in the locations suggested by Figure 1, although several older Portuguese pieces may have had *cruzetas* with only three arms, and it is possible that the Philips brothers used a design with two horizontally-opposed supporting arms.

Nevertheless, it is clear that the founders who produced *Sacramento*'s Portuguese cannon and her four newest English guns worked within the same tradition of *cruzeta* design and placement. The Dutch cannon are another story. The 4½-pounders seem to have had four-armed *cruzetas*. That may also be true of the Conrad Wagwaert 20-pounder, though there were no holes and I found magnetic indications in only one spot. The two remaining Dutch guns

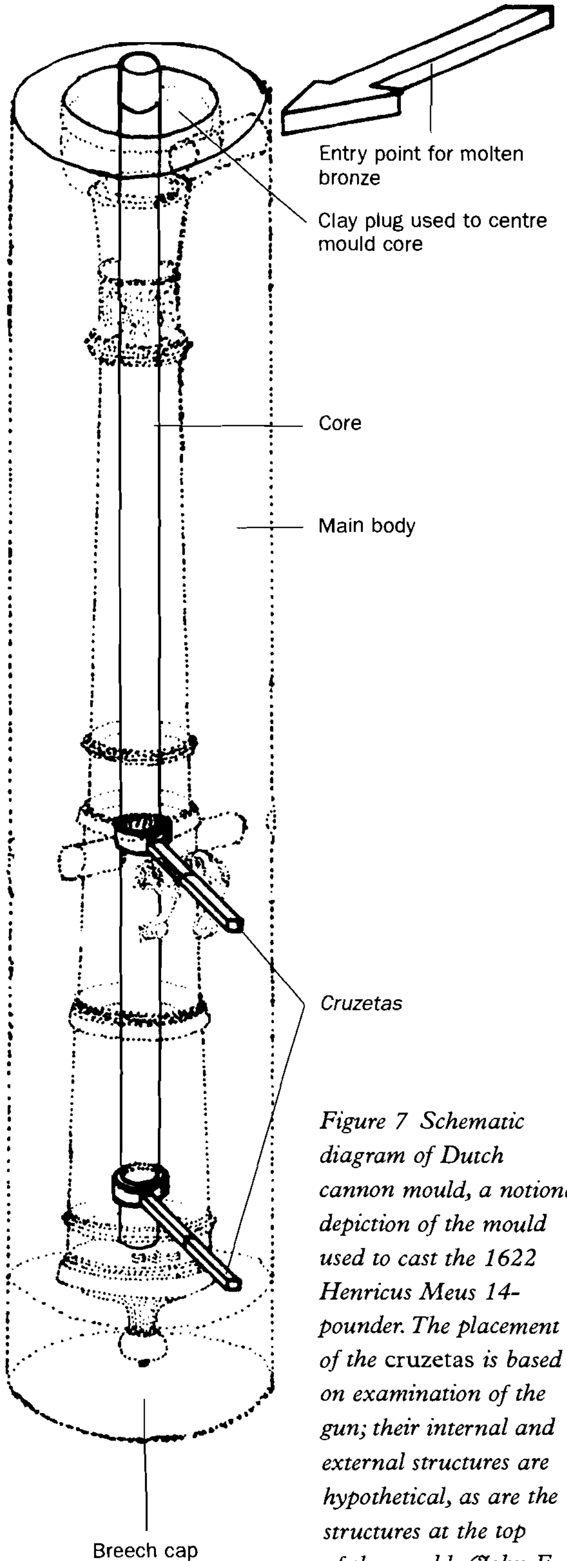


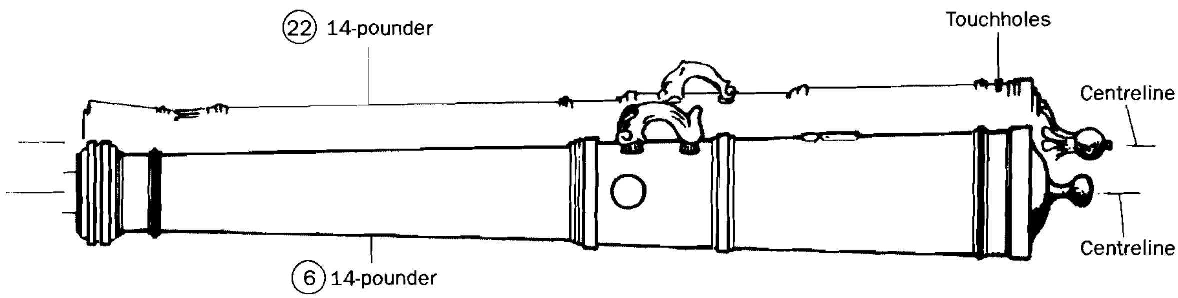
Figure 7 Schematic diagram of Dutch cannon mould, a notional depiction of the mould used to cast the 1622 Henricus Meus 14-pounder. The placement of the cruzetas *is based on examination of the gun; their internal and external structures are hypothetical, as are the structures at the top of the mould. (John F Guilmartin, Jr)*

were cast with an embedded internal iron structure in the middle of the barrel. The 1622 piece by Henricus Meus has two square holes measuring about 1 × 3/4 inches (2.5 × 2.0 cm) on top of the barrel, one forward of the touchhole and the other between the dolphins. The 1634 Assuerus Koster 20-pounder shows evidence of a conventional *cruzeta,* but there are also magnetic indications of a mass of ferrous material beneath the surface between the dolphins: based on the detection range of my magnet, it lies within three-quarters of an inch of the surface; the implications are unclear. Figure 7 is my best guess at the manner in which the Henricus Meus piece was cast.

What function did the iron structure within the Assuerus Koster piece serve and how was it positioned during casting? Could it have been part of a structure intended to reinforce the bronze in the manner of steel reinforcement bars in concrete? We can only speculate. All we can say with certainty is that some Dutch founders used a second *cruzeta*-like structure embedded in the cannon halfway down the barrel.

A final difference between Dutch and Luso-English practice lies in ornamentation. To a gun, the Dutch pieces are encrusted with elaborate raised floral ornamentation, inscriptions and nautical motifs. The presence of elaborately decorated guns as functional booty on the gundecks of an enemy ship shows that such ornamentation was not confined to a handful of select presentation pieces. Precisely what to make of this is unclear, except to say that the Dutch gunfounder's methods and ethos and those of his customers plainly differed from those of their English and Portuguese contemporaries.

Comparison of the only two 14-pounders recovered (Figure 8), one Portuguese and the other Dutch, suggests that the Portuguese advantage in foundry practice was of fairly recent origins, though we



Comparative data

Gun	Barrel weight	Relative length of barrel	Weight of barrel per pound of ball	Thickness of barrel wall at base of bore
1622 Henricus Meus	3548 pounds[a]	23.3 calibres	247 pounds	1.09 bore diameter
Undated Dias Bocarro	3247 pounds	23.9 calibres	232 pounds	1.11 bore diameter

a Based on the calculated volume of the barrel and a metal density of 516 lb/ft^3, about the same as that of piece number 24, the Assuerus Koster 20-pounder.

should not overgeneralise from a small sample. The two guns are remarkably similar in shape and, although the Portuguese piece has a slight advantage in efficiency, the difference is surely within the margin of error in my calculation of the Dutch gun's volume. As we have already indicated, the internal structures of the two guns were dramatically different. The lesson is that founders could arrive at the same destination by very different routes. Seventeenth-century cannon founding, in short, was anything but standardised.

Sacramento's smaller Portuguese pieces (Figure 9) are clearly products of the same tradition as its Portuguese 28- and 26-pounders and were probably cast in the same foundry, but there are intriguing differences. Of the six Portuguese 11-pounders, only three appear to be of a quality comparable to that of the larger pieces by Matias Escartim and Antonio Gômes Feio. One of these was cast by Gômes Feio himself. Though they bear no founder's mark, the other two are clearly closely related to the larger guns. Their external shape and details are virtually identical, as are the royal crest and monogram of Dom João III. That the smaller pieces bear no founder's mark probably reflects the greater importance attached to the larger pieces and the greater difficulty and danger in casting them. The larger pieces were no doubt cast under the eye of the master founder, while the smaller pieces were entrusted to understudies or apprentices. This hypothesis is reinforced by the fact that the only 11-pounder to bear a founder's mark, A.G.F., is the lightest of the six by some 150 pounds, despite probably having been cast at least a decade earlier when smaller cannon presumably commanded a master founder's attention.

Figure 8 Comparison of Santíssimo Sacramento*'s two 14-pounders: the Henricus Meus piece 22, cast in 1622, the oldest of* Sacramento*'s five Dutch guns; and the undated Pedro Dias Bocarro piece 6, which appears to be the oldest of* Sacramento*'s Portuguese guns, based on its proportions. In addition, the simple and relatively small royal crest atop the breech is unlike those on* Sacramento*'s other Portuguese guns, but is very similar to those on the two oldest English pieces (Figure 11) which I believe to have been cast prior to 1580. (John F Guilmartin, Jr)*

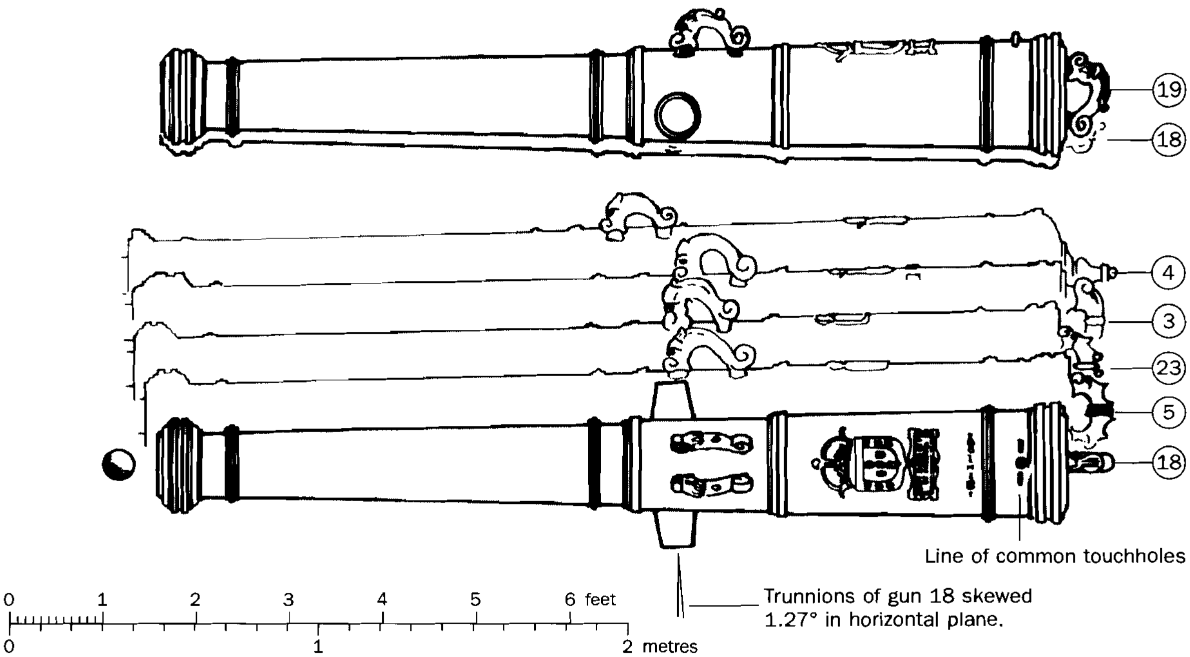


Figure 9 Santíssimo Sacramento*'s Portuguese 11-pounders. Guns 18 and 19, cast with the royal monogram of Dom João III (reigned 1640–56) are virtually identical. The other four are undated, but bear the Portuguese royal arms. (John F Guilmartin, Jr)*

The remaining three 11-pounders are a mixed bag. They all appear to be older than the other three, but do not differ dramatically in proportions or weight.

The Portuguese had apparently found guns of this size and ball weight to be useful well before the mid-1600s and had standardised on them to the degree possible. If our *galeão*'s gundecks are an accurate indication, the English may have standardised earlier along similar lines, for three of *Sacramento*'s nine bronze 11-pounders are English.

Sacramento's English ordnance

Beyond informing us of the shared English and Portuguese penchant for precisely weighing naval ordnance, *Sacramento*'s English guns (Figures 10 and 11) have much to tell us. They show unequivocally that good bronze ordnance could have a remarkably long service life, even in a harsh salt-water environment; the youngest of the four dated pieces (Figure 10) was over 70 years old when *Sacramento* went down. That was unexpected. They also provide evidence that English foundry practice in the 1590s was world class. The two pieces by John and Richard Philips have less bronze per pound of projectile than Dutch 20-pounders cast four to five decades later. The two later pieces by George Elkine are less efficient, but are still impressive. The four were *Sacramento*'s shortest gundeck pieces, with barrels at the low end of the ballistic optimum; if we calculate the volume of the powder charge as before, their projectiles would have travelled between just over 7 feet (the 11-pounders) and 7½ feet before exiting the muzzle. In line with our hypothesis, the Philips brothers' newer 20-pounder was slightly

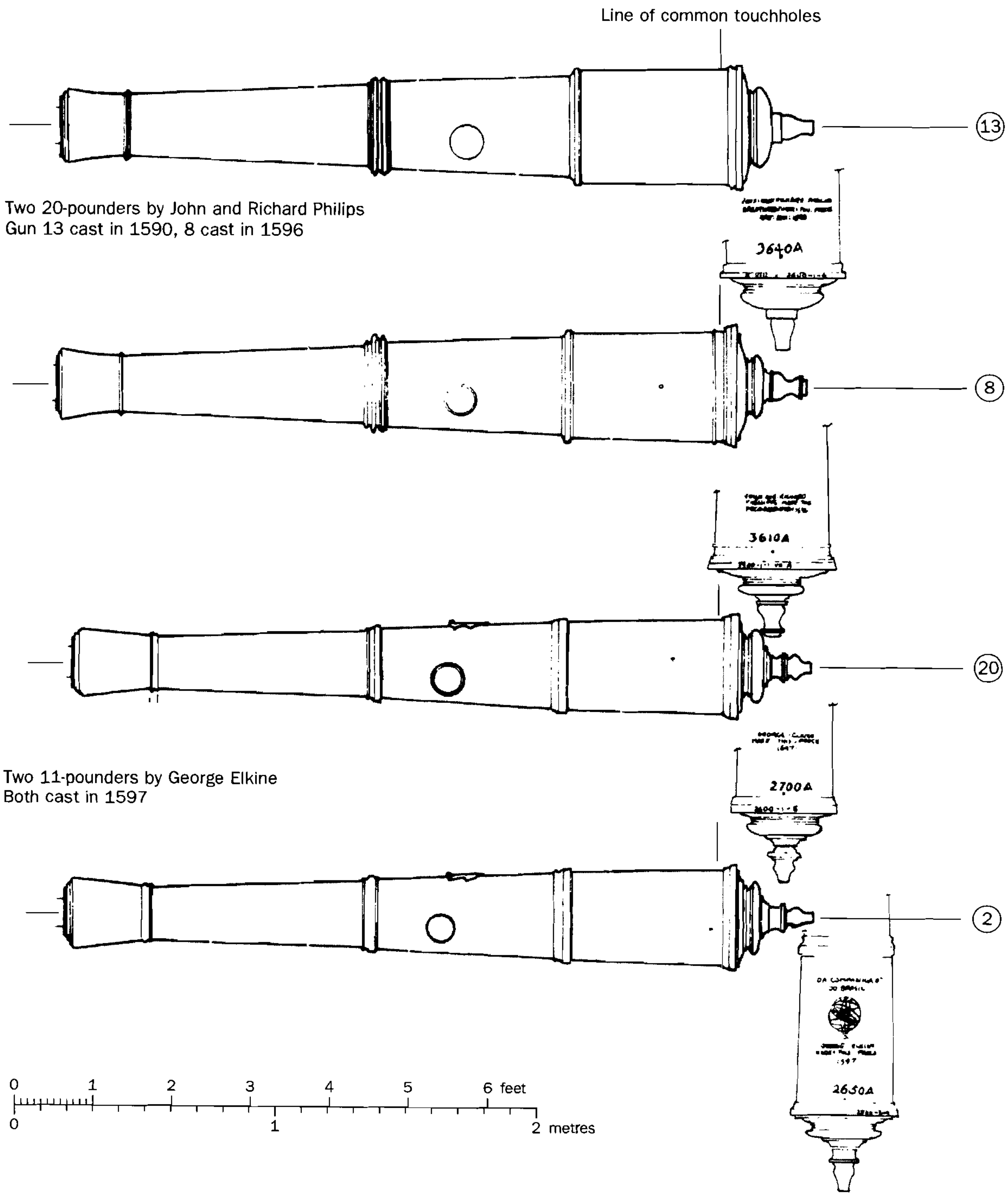


Figure 10 Dated English guns by John and Richard Philips and George Elkine.[25] *Note the double weight markings atop the breeches. The Portuguese weight markings are in a slightly different style from those on later pieces. (John F Guilmartin, Jr)*

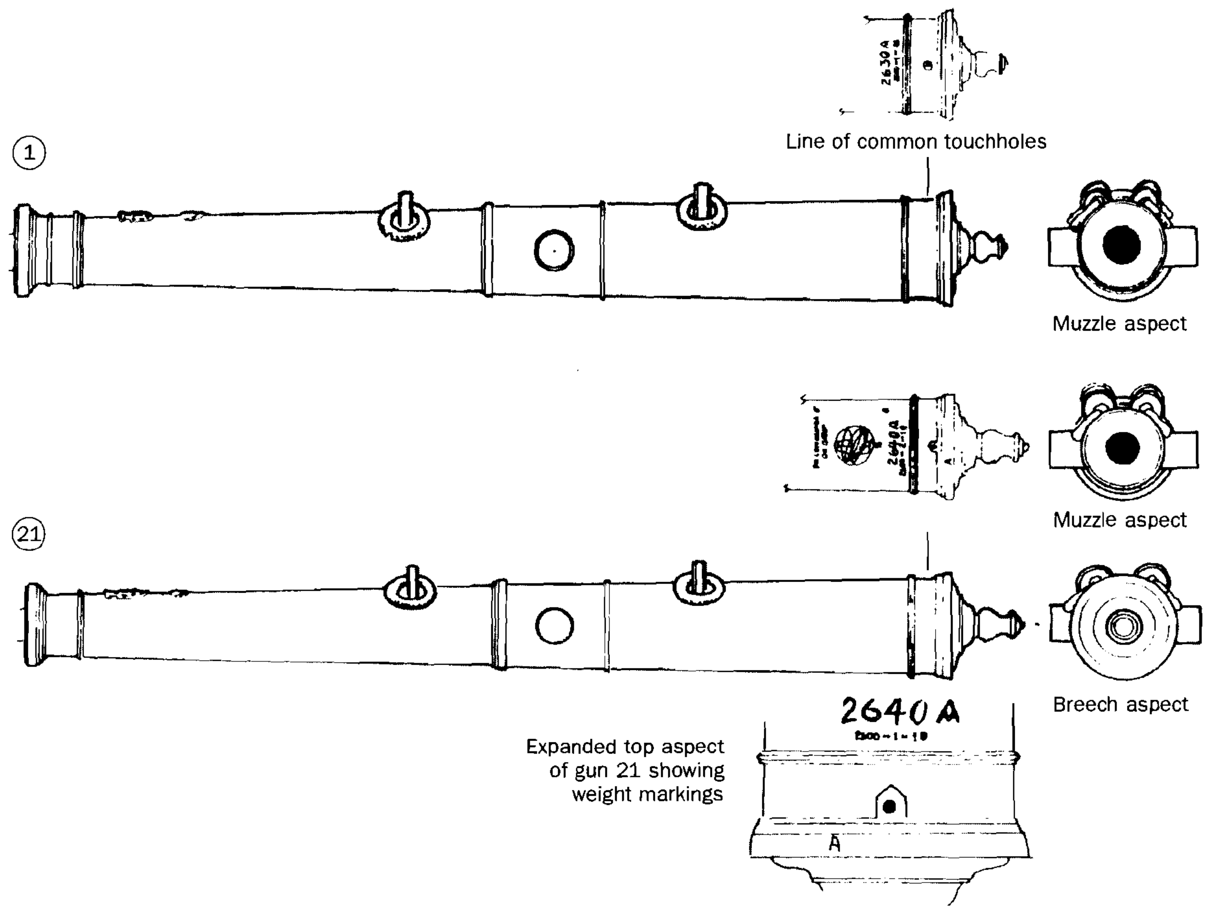


Figure 11 Santíssimo Sacramento*'s two undated English guns. These two pieces, an 11-pounder (top) and an 8-pounder (bottom) are similar in external form, though they differ in detail. Both have the Portuguese royal crest cast atop the barrel near the muzzle; both have the inscription 'DA COMPANHIA G*[L] *DO BRASIL' and an armillary sphere with the logo 'SPERO IN DEO' incised atop the breech. (John F Guilmartin, Jr)*

more efficient in pounds of bronze per pound of projectile than the older one even after, as we suspect, the older piece was rebored to a larger calibre.

Sacramento's oldest English pieces (Figure 11), identified as such by their weight markings, great length and archaic features, particularly the lifting lugs and rings atop the barrels, are intriguing. They bear no founders' marks and are not dated, but are plainly much older than the others, corresponding in size and shape to demi-culverins from the wreck of the *Mary Rose*, sunk in 1545.[26] The Portuguese royal crest is cast atop their muzzles, suggesting that they were founded before Portugal's absorption by Habsburg Spain in 1580. Their form is older still, bearing distinct similarities to early-sixteenth-century Portuguese and Ottoman pieces. Showed them out of context and asked to date them, I would estimate that they were cast between 1500 and 1530.

They were apparently cast with conventional four-armed *cruzetas* set a bit further forward than later practice, but there were strong magnetic indications of ferrous material beneath the bronze surface all around the breech caps, within the trunnions and in the lifting lugs. Curiously, the lifting rings appear to be entirely of bronze. What purpose the internal iron structure served and how it was held in place during casting is a mystery. Was the internal iron meant to strengthen the pieces, or was it there to displace more expensive bronze? We can only speculate. Particularly vexing is the question of how the cast bronze rings were mounted on the lifting lugs. Surely they were not cast in place after the guns were broken out of their moulds. But the alternate hypothesis, that they were embedded in the moulds and the guns cast around them, seems even more improbable. All we can say with certainty is that, however it was done, it was done well, for the guns survived for an uncommonly long time. It is equally clear that the process had inherent drawbacks, for it was abandoned. The obvious hypothesis is that the process was both skill- and labour-intensive and gave way to cheaper methods.

Conclusions: the importance of nautical archaeology and the economics of gunfounding

In conclusion, our exercise strongly underlines the value of nautical archaeology. Had the bulk of *Sacramento*'s guns not been recovered under controlled circumstances, we would know substantially less about early modern naval ordnance and bronze gunfounding. Next, the heterogeneity of *Sacramento*'s gundeck provides clear evidence of a shortage of good ordnance, particularly heavy ordnance, on the part of the Companhia Geral do Comerçio do Brasil, and it is hard to imagine that any other part of Portugal's naval establishment was any better off. We know that Portugal initiated large-scale importation of Swedish cast-iron ordnance after throwing off Spanish rule in 1640, and it is likely that the bulk of *Sacramento*'s iron pieces were Swedish.[27] Swedish or not, the cast-iron pieces on *Sacramento*'s gundecks were there not because of superior technical qualities: they were there because of their low price. Conversely, *Sacramento*'s gundeck provides unimpeachable evidence of the high quality of mid-seventeenth-century Portuguese bronze ordnance and, indirectly, of its high cost. It also provides solid evidence of the excellence of sixteenth-century English bronze ordnance and at the same time of the remarkable longevity of well-cast bronze guns. Without the hard evidence raised by *Gastão Moutinho*'s divers, the notion that guns could remain in naval service from 70 to 90 years or more would have seemed improbable at best. Even if the pieces in question had not been in continuous service, their simple survival as operational pieces is both unexpected and informative.

Sacramento's four newest English pieces also provide hard evidence that the very best bronze guns of the sixteenth century were equal in quality to all but the finest of the seventeenth, contradicting the commonly held notion that technology advances in a steady, linear fashion. The wide variation in design and quality of *Sacramento*'s Dutch guns makes the same point. Indeed, one of the most powerful facts to emerge from the study of *Sacramento*'s guns is an awareness of the enormous variations in foundry practice as a function of time and place. These differences have implications at which we can only guess and merit additional study.

In addition to raising fundamental questions about early casting methods, *Sacramento*'s two oldest English pieces provide evidence that earlier foundry practice may have produced technically superior ordnance by labour-intensive methods that could not be retained in the face of the wage and price spiral of the late sixteenth and seventeenth centuries.

Finally, the degree of control that the best Portuguese and English founders exercised over the physical characteristics of their products represented on *Sacramento*'s gundecks suggests that historians have underestimated the early modern cannon founder. Moreover, the precision with which the English and Portuguese weighed their naval ordnance suggests that the early modern sailor, shipwright and gunner have been similarly underestimated. Their work was not based on elegant theories of internal ballistics, metallurgy or the relationship between stress and strain; nevertheless, their application of incremental development based on trial and error supported by close quality control was highly successful. We still have no satisfactory theoretical explanation for their success.

Notes and references

1 Information to the author from Admiral Carneiro, autumn 1978

2 Pernambucano de Mello e Neto, U, 'O galeão *Sacramento*', *Navigator* (Journal of the Serviço de Documentação Geral da Marinha, Rio de Janeiro), 13 (June 1976 – December 1977), pp3–40

3 'Os canhoes do *Santissimo Sacramento*', *Navigator*, 17 (January–December 1981), pp3–43, 44–82, in English translation

4 'The guns of the *Santissimo Sacramento*', *Technology and Culture*, 24/4 (October 1983), pp559–601

5 Pernambucano de Mello e Neto, U, 'The shipwreck of the galleon *Sacramento*', *International Journal of Nautical Archaeology*, 8 (August 1979), p215

6 Guilmartin, J F, Jr, *Galleons and Galleys* (London: Cassell, 2002), pp13, 210–11

7 Fox, F, *Great Ships: The Battlefleet of King Charles II* (Greenwich: Conway Maritime Press, 1980), contains a full treatment of the tactical dominance and lack of endurance and seaworthiness of the giant English three-deckers of the first- and second-rates of the 1652–77 Anglo-Dutch Wars and their Dutch and French equivalents. See p95 for the tactically decisive role of the largest English ships in the Second Anglo-Dutch War (1664–67) and p21 for their unwieldiness. The smaller 'rates' that were on occasion employed far from home had two ordnance allowances: an augmented establishment 'to be carried only during wartime [...] in home waters' (p187), which in practical terms meant during the relatively calm months of late spring and summer, and a reduced allowance for peacetime cruising and for extended operations on overseas stations in wartime.

8 English first-rates carried a main battery of cannon-of-seven, cast-iron guns designed to fire a 42-pound cast-iron ball, as did the largest second-rates. Both first- and second-rates had three full, enclosed gundecks; third-rates had two enclosed gundecks. English

third-rates carried main batteries of 32-pounders. In general, first-rates carried more than 80 guns, second-rates at least 70, and third-rates between 56 and 64.

9 Fox, F, note 7, Appendix III, 'Ordnance establishment of 1666', pp184–5

10 The limiting factor for very large high-velocity guns is the ability of the chamber to withstand the extremely high temperatures involved.

11 Guilmartin, J F, Jr, 'Ballistics in the black powder era: a cursory examination of technical factors influencing the design of ordnance and of the emergence of ballistics as an applied science', in Smith, R D (ed.), *British Naval Armaments*, Royal Armouries Conference Proceedings 1 (London: Trustees of the Royal Armouries, 1989), pp73–98. See also Guilmartin, J F, Jr, *Gunpowder and Galleys: Changing Technology and Mediterranean Warfare at Sea in the Sixteenth Century*, 2nd revised edn (London: Conway Maritime Press, 2003), Appendix 2, 'The external and internal ballistics of sixteenth-century cannon', pp295–303.

12 Guilmartin, J F, Jr, 'Ballistics...', note 11, p78. This view, supported by nineteenth-century tests as well as the empirical evidence provided by the guns themselves, replaces the generally accepted notion that the relevant metric was the length of the bore in calibres, that is in multiples of the bore diameter, with a maximum useful length of 18 to 20 calibres obtaining for guns of the sizes with which we are concerned here. Maximum useful barrel length was less for smaller cannon, since smaller barrels transfer the heat of the propellant charge to the atmosphere more efficiently, but the difference is relatively small for guns firing a ten-pound ball or larger.

13 Guilmartin, J F, Jr, *Gunpowder and Galleys...*, note 11, Appendix 3, 'The design and construction of bronze cannon in the sixteenth century', pp305–13. For experimental confirmation of the relationship between density and strength, see Rodman, T J, *Reports of Experiments on the Strength and Other Properties of Metal for Cannon...* (Philadelphia, PA: 1856), pp152–3, quoted in Guilmartin, J F, Jr, *Gunpowder and Galleys...*, note 11, Appendix 3, p307, n. 8: a 5.4-per-cent increase in density yielded a 52-per-cent increase in tenacity, a measure of resistance to shearing stress.

14 The incremental but steady trend in sixteenth-century cannon founding toward shorter, lighter guns has been exhaustively documented for the English case in Lewis, M, *Armada Guns: A Comparative Study of English and Spanish Armaments* (London: 1961).

15 The definitive study is de Beer, C (ed.), *The Art of Gunfounding: The Casting of Bronze Cannon in the Late 18th Century* (Rotherfield: Jean Boudriot Publications, 1991).

16 Lavery, B, *The Arming and Fitting of English Ships of War, 1600–1815* (London: Conway Maritime Press, 1987), pp84–5

17 Fox, F, note 7, Appendix I, 'List of ships in service, 1660–1685'

18 Fox, F, note 7, p134

19 Guilmartin, J F, Jr, 'The guns of the *Santíssimo Sacramento*', note 4, Appendix A, 'Linear regression analysis of double weight markings on *Santíssimo Sacramento*'s six english cannon', pp598–601

20 See, for example, Lewis, M, *Armada Guns: A Comparative Study of English and Spanish Armaments* (London: 1961), p219. The pound avoirdupois contains 453.6 g, the value usually given for the *arratel* is 459 g and that experimentally determined here is 465.2 g.

21 Number 13 is off by –88 pounds; the differences between the Portuguese and English weights of the other five are –11 pounds, –3 pounds, +11 pounds, +4 pounds and +1 pound, leading to the suspicion that number 13 was rebored to a larger calibre before it fell into Portuguese hands.

22 Douglas, H, *A Treatise on Naval Gunnery, 1855* (London: Conway Maritime Press, 1982), reprint, p475, gives the density of black powder. Powder in Douglas's day would not have varied in any significant way from seventeenth-century Portuguese corned powder. The weight of the charge is an estimate based on earlier practice given in Collado, L, *Platica Manual de Artilleria* (Milan: 1592). Collado specified a charge equal to the weight of the ball and powder charges became progressively smaller with time.

23 Rodman, T J, note 13, pp152–3, describes a test conducted on two 12-pound howitzers

cast eight to ten minutes apart from the same vat of molten metal that varied in the density of their bronze by 3½ per cent.

24 Biringuccio, V, *Pirotechnia*, trans. Smith, C S and Gnudi, M T (New York: 1942), based on the 1540 Venice edition, pp246–8

25 John and Richard Philips are mentioned in the Calendar of State Papers of 16 August 1588, as purveyors of cannon to the British Crown; George Elkine, who apparently died in 1604, is first mentioned in 1595 (Admiral Sir Terence Lewin, GCB, MVO, DSC, ADC, to Capitão-de-Mar-e-Guerra (RRm) Guedes, 14 June 1977, courtesy of Captain Guedes).

26 Examined by me in the Museum of the Royal Artillery Institution in the Rotunda at Woolwich, England, in 1975; the earliest date on these cannon is 1529, *Catalog of the Museum of Artillery, Part I, Ordnance* (London: 1963), p7. This impression is sustained by the appearance of dated cannon in the collections of the Museu Militar, Lisbon; the Museo del Ejercito, Madrid; and the Askeri Musesi and Deniz Musesi, Istanbul.

27 Portugal imported 127 metric tonnes of iron ordnance from Sweden in 1661, and by 1694 was Sweden's biggest customer; see Cipolla, C M, *Guns, Sails and Empires: Technological Innovation and the Early Phases of European Expansion, 1400-1700* (New York: 1965), p56.