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The Athlit ram bronze casting reconsidered: scientific and technical re-examination

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Abstract

Visual examination and advanced analytical techniques were used to re-examine the large Hellenistic bronze naval ram found in 1980 at Athlit Bay, south of Haifa, Israel. The aim was to reevaluate the method used to manufacture this massive bronze casting. In contrast to an earlier study of the ram that suggested that it was manufactured using the sand-casting method, a technique not otherwise known prior to the late Medieval period, the current study suggests that the ram was manufactured by the lost-wax technique commonly used during the Classical and Hellenistic periods. Newly gathered data point to a selective use of the direct and indirect lost-wax casting methods to manufacture different parts of the ram, and allow postulation of the innovative use of the direct lost-wax casting method to fulfil the ram design requirements.

Keywords: Israel; Athlit Ram; Naval ram; Bronze casting; Copper alloys; Classical-Hellenistic

1. Introduction

The discovery of a large Hellenistic naval ram in 1980 in Athlit Bay, south of Haifa, Israel, provided a rare opportunity to study both the technology of bronze casting and the methods of warship construction during the Hellenistic period.

The ram is 2.26 m long, 0.95 m high and weighs 465 kg (Fig. 1), far exceeding other surviving naval rams in size. As such it holds a unique position as one of few large cast bronzes manufactured for practical rather than votive or commemorative purposes.

Initial metallurgical analyses of the ram, made shortly after its recovery, led to the conclusion that it was cast horizontally on its side in a two-part sandbox [7:40–50]. Although open moulds made of sand or of sand and clay mixture may have been used for casting metal objects in the Chalcolithic and possibly also for casting copper and tin ingots during the Late Bronze Age [5,33] there is still no evidence for sand-casting in antiquity. The use of the sand casting method had not otherwise been documented prior to the late Medieval period [15:475,16:628,27:23]. Such a conclusion, therefore, contradicts our understanding of Classical and Hellenistic bronze casting technology, which is based on considerable archaeological evidence. The record consistently points to the use of clay-based materials for mould-making and casting of both small and large bronzes by the lost-wax process [12:54–55,17:125–126,18:789].

The initial study of the Athlit ram at Haifa University was conducted before the removal of the hull timbers preserved within, and consequently only the exterior surface details were recorded. With the ram now conserved and the hull timbers completely removed, it was possible for the first time to visually examine all of its surfaces, including its interior.

Given the importance of the Athlit ram, the author felt that a thorough reevaluation was warranted. This

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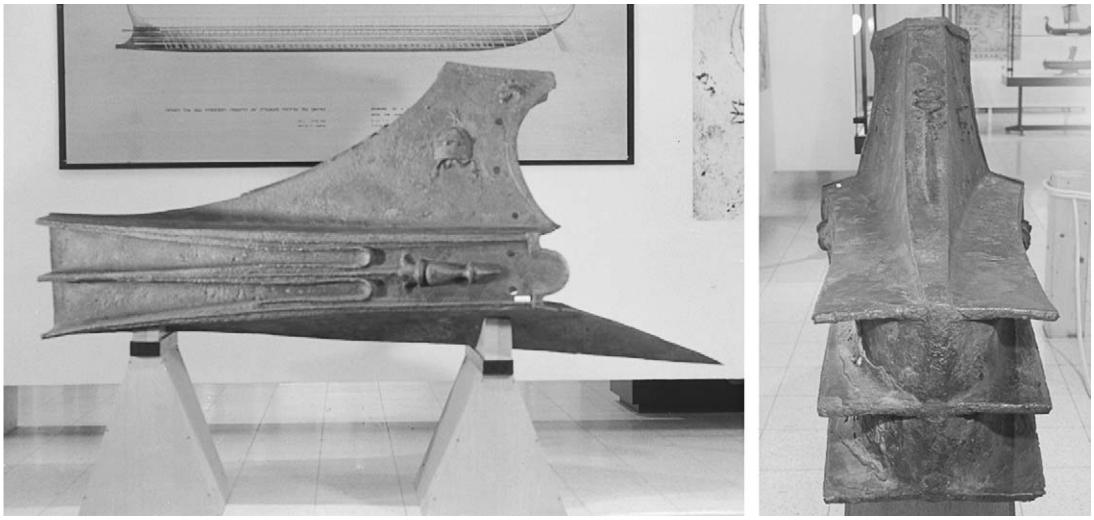


Fig. 1. The Athlit ram on display at the National Maritime Museum, Haifa, Israel. (Photograph by the author)

examination, combined with analytical techniques such as inductively coupled plasma atomic emission spectrometry (ICP-AES), radiography and metallographic cross-sections, produced a wealth of new information.

This paper presents some of the initial results of the study. These focus on newly discovered technical information, alloy analysis and the reevaluation of the casting technique used to manufacture the ram in the context of ancient ship construction.

2. Description and observations

In describing the Athlit ram it is helpful to refer to its three functional parts as defined by Steffy during his initial study: *driving centre*, *bottom plate and cowl* [28:11, fig. 2.7] (Fig. 2).

The *driving centre* housed the main horizontal bow timbers and delivered the ramming blow through the head at its forward end (Fig. 3). This impact area is composed of three robust fins merging into a solid wall at the centreline of the ramming head.

The *bottom plate* is an undecorated concave cover that protected the bow's lower timbers. On its exterior the bottom plate centreline carries a flat ridge-like feature, the reverse of which forms the bottom plate channel. The channel flattens out as it approaches the ramming head, while the outer surface maintains the ridge structure throughout its length. This in turn transforms the bottom plate ridge into a solid bronze bar which reinforces the ramming head area.

The *cowl* sheathed the vertical bow timbers. It consists of a flat nosing that curves upward to meet the stem of the ship, and a pair of chariot-shaped sides that flare outward along the hull's side planking. Four bronze bolts on each side fixed the cowl to the stem.

2.1. Other features: surface

Visual and radiographic examination of the ram shows no evidence of parting lines, a common feature on bronzes that were cast in refractory piece moulds (for examples of such marks, see [27:7, fig. 4; 12:43–46, fig. 5]. In addition, the examination does not show any evidence of joints between separately cast elements, commonly seen on many large-scale classical and Hellenistic bronze statues (Figs. 4 and 5). Altogether this evidence suggests that the ram was cast as one unit using a single-piece mould. The radiographic analysis also makes it possible to identify features such as chaplet holes, repairs, and variations in wall thickness throughout the cast.

The interior surface of the ram follows its external shape, with the exception of the symbols, which are flat on the reverse, and the bottom plate channel. A comparison between the ram's port and starboard sides indicates a lack of symmetry, both in overall dimensions and in artistic rendering. The most obvious differences are observed in the trough sideplates (Fig. 6).

2.2. Decorations

Close examination of the three paired symbols decorating the ram's side walls—an eagle head; a *pileus* surmounted by an eight-pointed star, and a decorative handle device—shows that they are positioned asymmetrically, and that they differ slightly in their design. In order to better understand the technique behind these decorations each pair of symbols was compared using a set of measurements to identical points, a technique commonly used in the comparative study of identical bronzes [11:136–137,18:796–797]. The measurements show significant dimensional variations between the two eagle heads, but nearly identical measurements for the

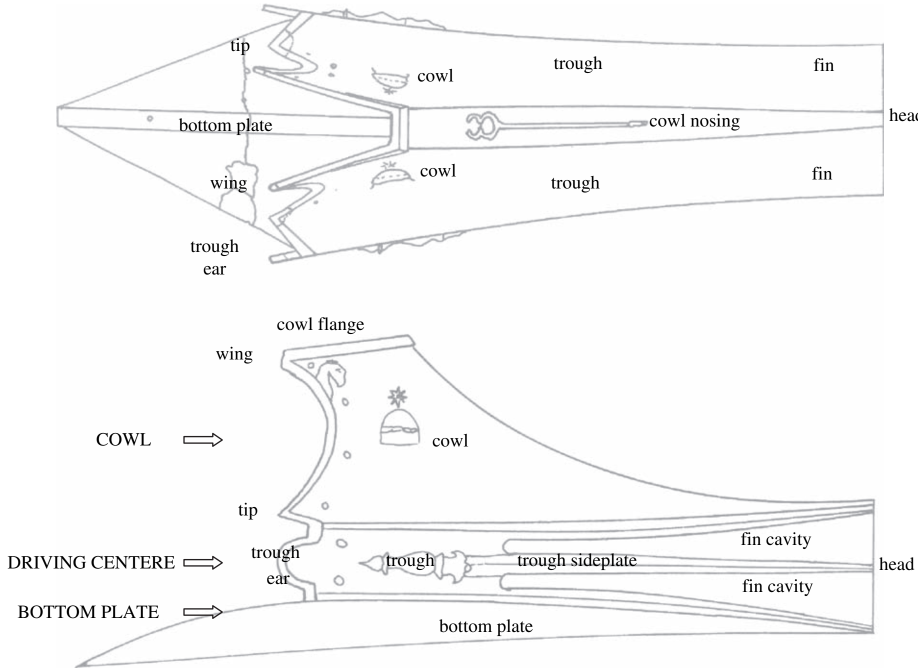


Fig. 2. Identification of the ram areas. (After Steffy [28:fig. 2.7])

handle devices and *pilei* (Tables 1a–c). Altogether, this evidence suggests that the *pilei* and handle devices were made in moulds which allowed the production of identical positives.

An indication of the use of the technique, often referred to as indirect casting, elsewhere is evidenced by a large collection of plaster moulds (probably of a first century BC date) from bronze workshops in Saqqarah and Memphis in the Cairo Museum [6:i–xiii]. The moulds were used to make positives in wax, which were then attached to a primary wax model, to be cast as a single unit.

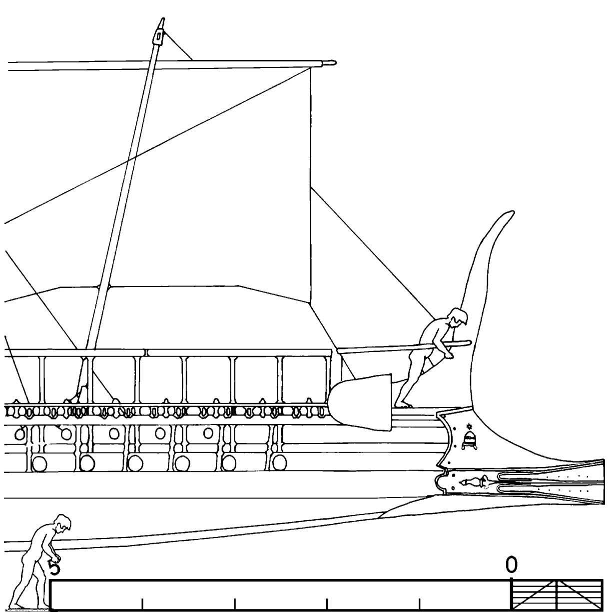


Fig. 3. An artistic rendering illustrating the position of the Athlit ram on the bow of its warship. (Illustration by Bilge Güneşdoğdu Akman and the author)

2.3. Bronze studs

Two pairs of circular bronze studs are located on the exterior of the bottom plate slightly aft of its mid-point (Fig. 7). The purpose of these studs is not entirely clear, but it is possible that they are the remnants of lugs for attaching ropes used to haul the ship up slipways. Their locations fit Coates' proposal that ropes would have been secured to the ram near hauling height and as far forward as possible to facilitate the hauling process (Coates, 2002, personal communication). Similar protrusions are also visible on the preserved portion of the bottom plate of the naval ram currently on display at the Piraeus museum [31:30–31, pl. 1].

2.4. Wall thickness

The radiographic analysis of the ram revealed significant variations in the wall thickness throughout the cast. The most noticeable of these are seen in the bottom plate and fin cavities.

The wall thickness of the ram was measured by Steffy at 24 locations, and was found to range in most areas between 0.7 and 1.0 cm [28:11]. The flanges, ribbing, fins, and the area around the head are significantly thicker. Additional measurements taken during the current study

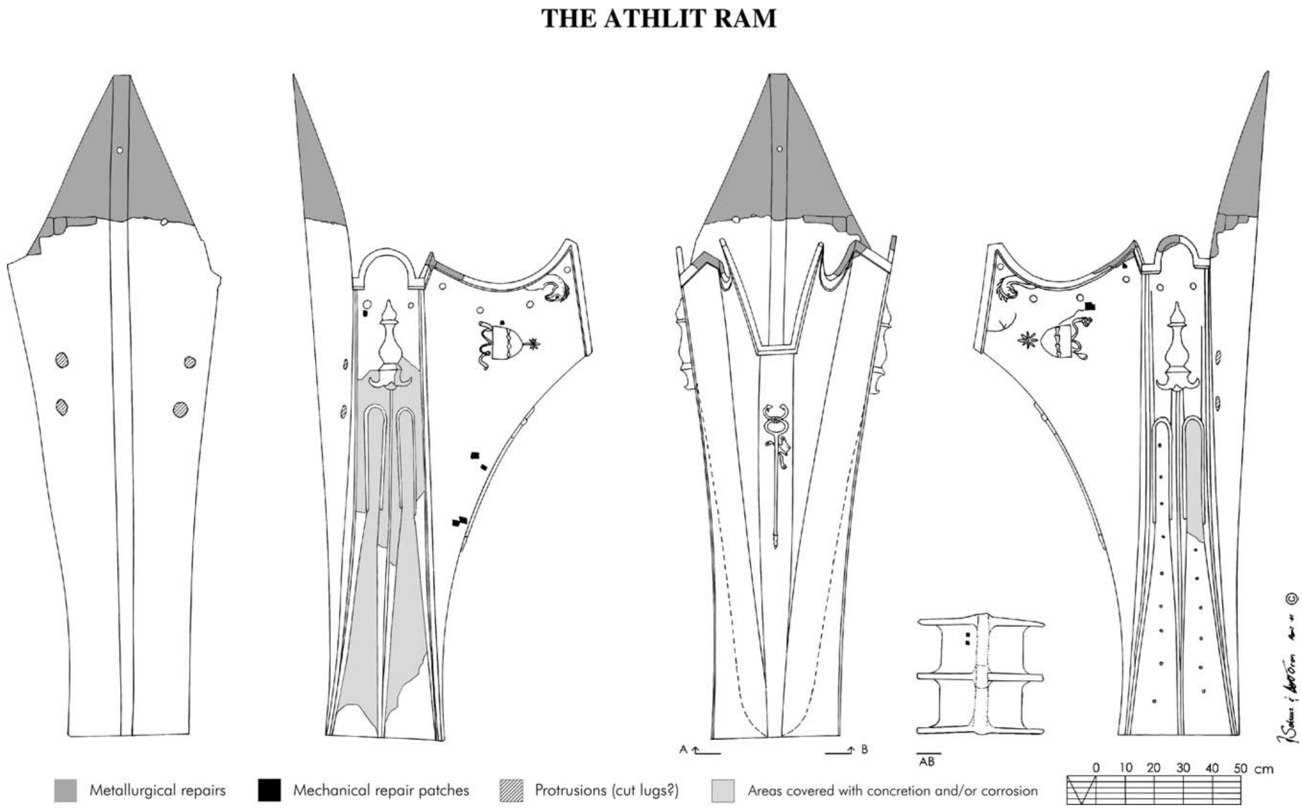


Fig. 4. The Athlit ram drawing. (Drawing by A. Schreur and the author)

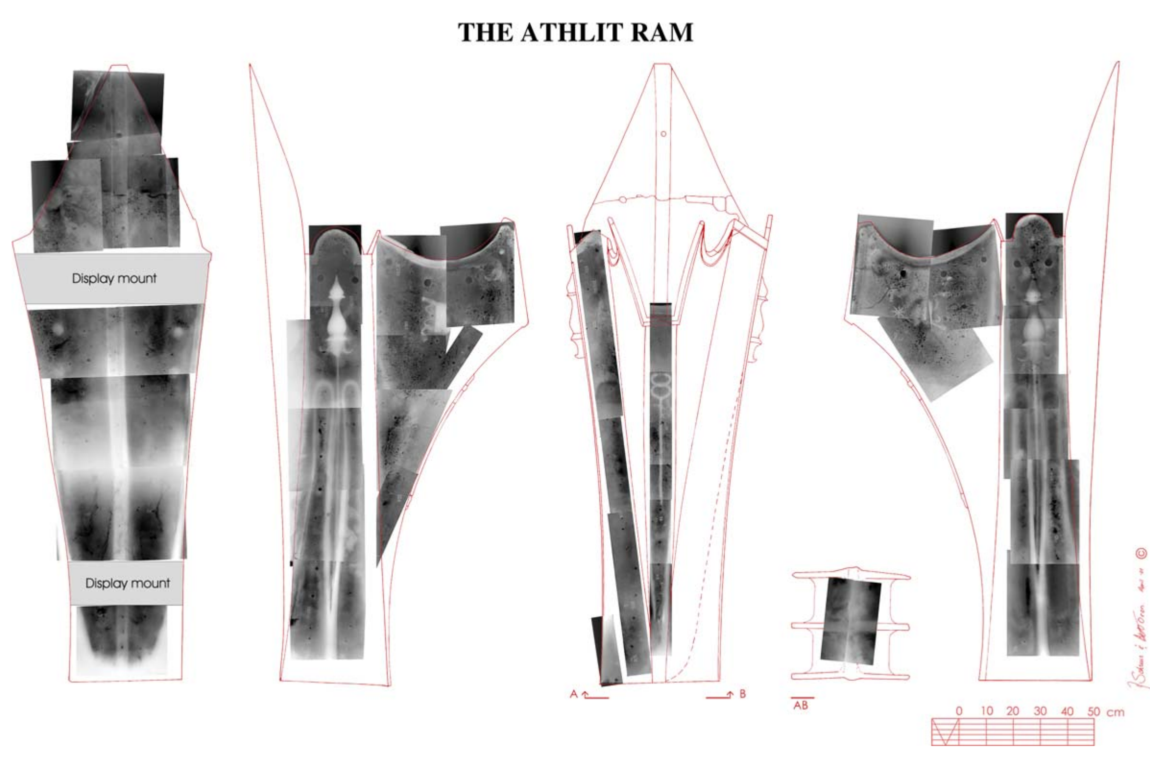


Fig. 5. The Athlit ram radiographic photomosaic. (By the author)

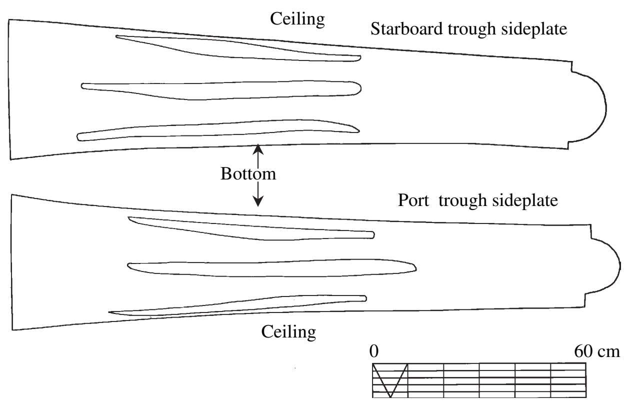


Fig. 6. The interior of the sideplates showing the dimensional variations in the plates and fin channels. (Drawing by A. Schreur and the author)

indicate longitudinal variations ranging from 0.7 to 3.5 cm along the trough ceilings, and from 0.9 to 4.1 cm along the bottom plate, with an overall increase in wall thickness towards the ramming head (Fig. 8). This section of the ram could not be measured directly, due to heavy encrustation still adhering to its interior; however it was calculated by Steffy to be 6.8 cm thick.

2.5. Chaplet holes

A series of square holes, averaging 4 by 4 mm, are distributed at regular intervals along the port fin cavities. Radiographic analysis confirmed the presence of an identical set of holes on the starboard side under the concretion that still covers that part of the ram (see Fig. 5). The analysis also reveals that many more holes of similar appearance are distributed at regular intervals throughout the entire surface of the cast. The square cross-section of the holes and the iron oxide found in some of them, together with evidence from other cast bronzes, indicate that they are chaplet holes, and not core spacers as suggested by Eisenberg. Chaplets are commonly used in the casting of hollow bronzes. They consist of iron or bronze rods inserted through the wax model walls into the core. The back ends of the rods are held in place by the investment mould, thus affixing the core to the outer mould walls, and keeping it in place inside the mould cavity during casting.

2.6. Casting faults and repairs

The ram seems to be extensively flawed, containing casting faults, such as cracks, blow-holes and incompletely cast areas. Most of these flaws are located in the after sections of the ram, including the cowl, the troughs, and the tailpiece. The flawed aft section of the ram stands in sharp contrast to the ramming head section, which appears almost flawless. This observation may hint that the ram was cast vertically, with the ramming head pointing down. Such an orientation may account for the accumulation of gas bubbles at the upper sections of the ram mould, and may also explain the incomplete casting of the rear sections of the ram, possibly due to a fast cooling rate or gas-trapping, both of which would have left the upper parts of the mould lacking in metal.

Visual examination of the ram surface and the radiographic analysis indicate that the ram was repaired extensively soon after its casting, using mechanical and metallurgical methods. The majority of the chaplet holes on the ram were covered by rectangular bronze patches, which were hammered into corresponding recesses cut above each one of the chaplets. Incompletely cast areas, such as the cowl edges and trough ears, as well as the entire tailpiece, were repaired by the metallurgical method known as 'casting on'. This is done by forming a clay mould over the missing area and then filling it with bronze. The repair techniques observed on the Athlit ram are well documented, and are common features of many Classical and Hellenistic bronzes [9:46–47,10:112,12:71, 14:14–22,21:98,25:71,30:115, figs. 32–33].

2.7. Surface marks and geometry

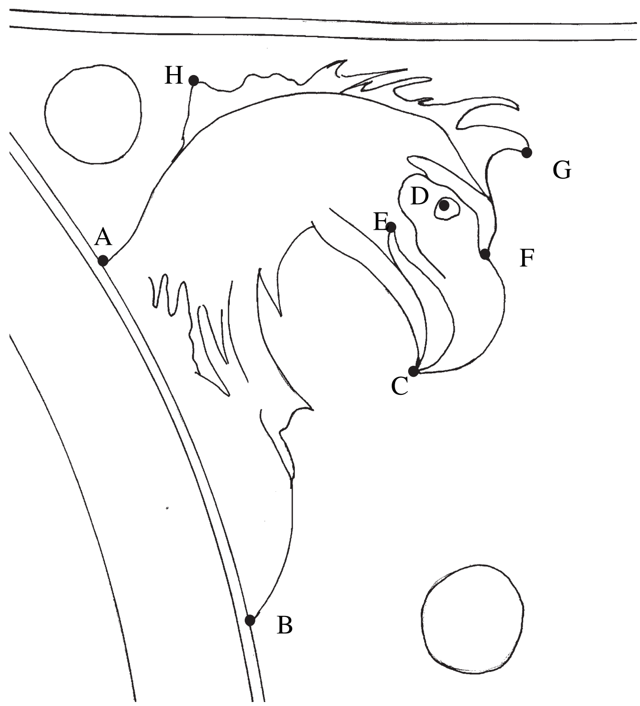
At least two sets of recessed marks are visible on the inside of the bottom plate. The first set crosses the bottom plate (Fig. 9A). The second set, of a much finer nature, begins at the middle transverse mark, and extends forward at an oblique angle towards the bottom plate channel (Fig. 9B). Similar marks have been observed on many hollow cast bronzes, where they are normally associated with the seam lines originated by joining the wax sheets during the construction of the model [9:46, pl. 20.2,10:107–188, fig. 7,12:35, pl. 3-4, 18:789,22:179–181].

An examination of the ramming timbers, in storage at the Israel National Maritime Museum in Haifa, shows a similarity in shape between the underside of the ramming timber and the contours of the bottom plate. This observation points to the intimate relationship between the ramming timbers and the bronze casting, and corroborates Steffy's initial observation that several features on the ram, particularly at the wale areas and nosing, mirror the geometry of the ramming timbers found within [28:38–39, fig. 2-24].

3. Chemical analysis of the ram

The main goal of the chemical analysis of the Athlit ram was to characterize its alloy composition to permit comparison with other Classical and Hellenistic bronzes. It was hoped that the analysis would also clarify certain technical problems, such as the nature of the repaired

Table 1
(a) Eagles; distance between points; (b) Pilei; distance between points and elevation measurements; (c) Handle Devices; distance between points and elevation measurements



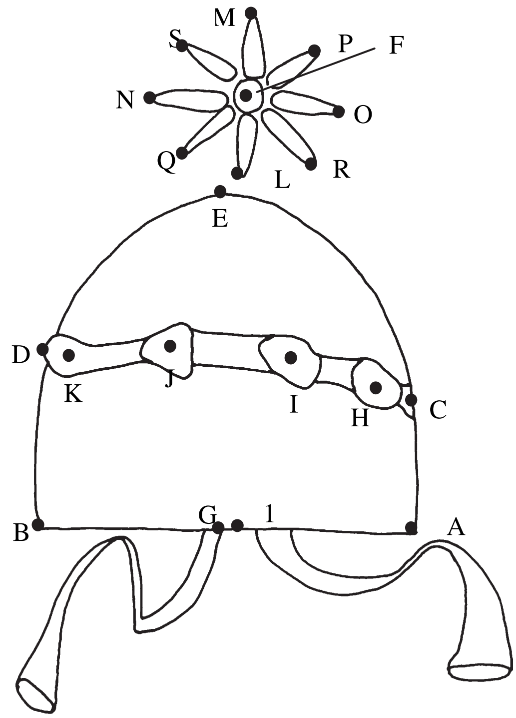
(a)	Distance between points	Starboard (cm)	Port (cm)
1.	A-B	9.70	9.03
2.	A-H	Concretion	3.90
3.	B-C	7.36	5.55
4.	C-D	3.70[a]	3.60[a]
5.	C-G	6.30	5.70
6.	D-E	1.6[a]	1.45[a]
7.	D-G	2.93[a]	3.17

sections and the relationship between the main casting and its decorations.

The chemical analysis was conducted using inductively coupled plasma atomic emission spectrometry (ICP-AES) with a Perkin Elmer Plasma 400 instrument at the School of Chemical, Environmental and Mining Engineering at the University of Nottingham, UK. The calibration of the instrument was accomplished using synthetic multi-element standards matched for total dissolved salt and acid content [13]. This type of analysis requires the removal of a small metal sample, which is dissolved, in concentrated acid and diluted, prior to analysis, up to a standard volume (typically 25 ml) to ensure a broadly standard dilution factor. The sample was collected by drilling a small hole (0.1 cm) in an inconspicuous area of the ram and collecting the drillings, after discarding the first millimetre or so in order to avoid contamination of the sample with unrepresentative material and corrosion products (the low totals in Table 2 are probably due to such unavoidable contamination). A total of ten samples weighing approximately 25 mg each were collected from selected parts of the ram for chemical analysis.

In most analyses of ancient metalwork, it is usual to run standard alloys of known composition alongside the study samples in order to assess the precision (or reproducibility) and accuracy (i.e. how close an analysis is to the true composition) of the procedure. Two runs of certified standard reference material (183/3 standard gunmetal) at the beginning and end of the analysis were used. They indicated an instrumental precision of $<3\%$ for all elements above detection limits, with figures worsening as the detection limit was approached. The actual precision of the analysis (reproducibility of a given analysis by element) is approximately 1–2% for major elements ($>1\%$), 5–10% for minor elements (0.05–1%) and 10–20% for trace elements ($<0.05\%$). Accuracy, as determined by the certified reference material, is 1–5% for major and minor elements, and about 10% for trace elements, with this figure again worsening as the detection limit for the particular element in question is approached.

Table 1 (*continued*)

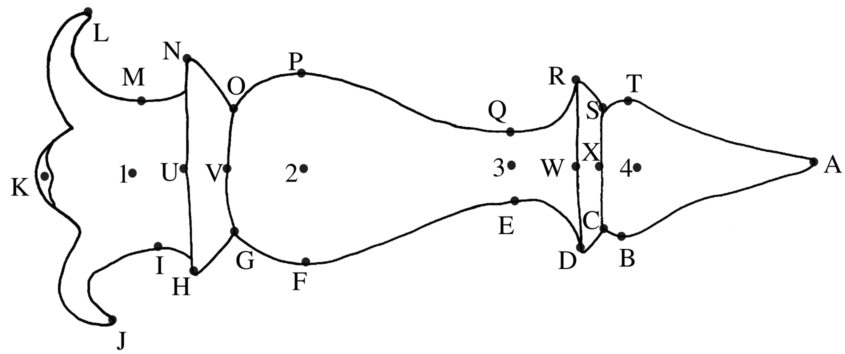


(b)	Distance between points	Starboard (cm)	Port (cm)
1.	A-B	11.88 concretion	11.16
2.	A-C	4.80[a]	5.10[a]
3.	B-D	5.00	4.67
4.	A-E	11.96[a]	11.95[a]
5.	B-E	12.70	12.30
6.	G-E	10.96[a]	11.06[a]
7.	H-I	3.50[a]	3.6[a]
8.	I-J	4.18	3.4
9.	J-K	3.0	point K does not exist on port
10.	F-E	3.20	3.77
11.	L-M	6.00[a]	6.00[a]
12.	N-O	4.75	5.60
13.	P-Q	5.00	5.67
14.	R-S	3.91	5.80
Elevation at point			
15.	1	2.2 concretion	1.70

The results of the analysis are presented in Table 2. Samples 2, 4, 5 and 9 are especially close (except the tin level in sample 9 which will be discussed below) in terms of their composition and, because of their locations, can be reliably regarded as representative of the metal composing the main casting of the ram. An average value calculated from these data was used as a 'base' composition for the ram (Table 3). It indicates a major element distribution with mean values of 90.4% copper and 9.78% tin, with virtually no lead. This composition, when compared with the available analytical data for Classical and Hellenistic bronze statuary, places the ram well within the range of Classical and Hellenistic alloy types [12: table 2].

The distribution of trace elements, i.e. small amounts of other metallic elements which are geochemically related to the parent metal used in the casting, in the samples from the Athlit ram permits some discussion regarding its fabrication history. When the individual values for each trace element in each sample are subtracted from this norm and compared, it becomes evident that the variance from the norm is very small—less than $\pm$ 0.025%—except in one sample, in which the amount of zinc is greater than the norm by 0.06% (Fig. 10). When the same calculation is made for the other samples, taken from repaired areas and patches (samples 3, 7, 8 and 11), a different picture emerges (Fig. 11).

Table 1 (*continued*)



(c)	Distance between points	Starboard (cm)	Port (cm)
1.	T-B	5.40[a]	5.60[a]
2.	S-C	5.50[a]	5.60[a]
3.	R-D	5.46 concretion	6.8
4.	Q-E	2.63[a]	2.66[a]
5.	P-F	7.34[a] corrosion	7.52[a]
6.	O-G	Concretion	5.76
7.	N-H	Concretion	8.68
8.	M-I	Concretion	6.10
9.	L-J	Concretion	12.30
10.	K-U	5.5	6.05
11.	U-V	1.77[a]	1.70[a]
12.	V-W	14.50[a]	14.20[a]
13.	W-X	0.72[a]	0.70[a]
14.	X-A	7.40	8.60
Elevation at points			
15.	1	Concretion	3.00
16.	U	4.50[a]	4.50[a]
17.	V	Concretion	2.60
18.	2	4.20[a]	4.20[a]
19.	3	1.80[a]	1.60[a]
20.	W	4.20[a]	4.20[a]
21.	X	2.90	3.30
22.	4	3.60[a]	3.50[a]

[a] Corresponding measurements on port and starboard $\leq$ 0.3 cm

In these samples, the variances from the norm are often considerably greater for certain elements, and therefore suggest that these repairs were made using metal originating from a different alloy batch. A comparison of the composition of a hammered repair patch (sample 11) to the norm for the main body of the ram shows a close correlation in trace element levels and suggests that the metal used for this patch was of the same batch used for the primary casting. However, samples 3 and 8, taken from the two small cast on repairs, differ from the norm in their trace element composition. They are also notable as the only samples containing a significant, though still very low, lead content (0.12% and 0.14%, respectively). The similar composition of the two samples suggests that they were made from the same batch of metal, which itself differed from that used for the main ram casting.

The most divergent sample was that taken from the repaired tailpiece (sample 7). This sample contains significantly higher levels of cobalt (0.140%), silver (0.030%) and antimony (0.023%). The lead content of this section is below detectable limits (<0.1%); however, its tin level is above the norm (10.32%). These variations again indicate the use of an altogether distinct metal batch for the repair of the tail-piece. The higher tin level may have been useful in lowering the melting point of the alloy and thus assisting in the repair process. This may also help to explain the higher tin level in sample 8 (11.11%), which was taken from a cast on repair. An increased tin level (12%) was also observed in a sample taken from the fin (sample 10), which also showed a high iron content (0.121%). It is possible that the increased iron level results from contamination caused by drilling through a blow hole that may have contained iron corrosion introduced by external leaching [23:1318]. The high tin level, however, raises some questions regarding this area of the ram. The radiographic analysis of the fin indicates exceptionally low

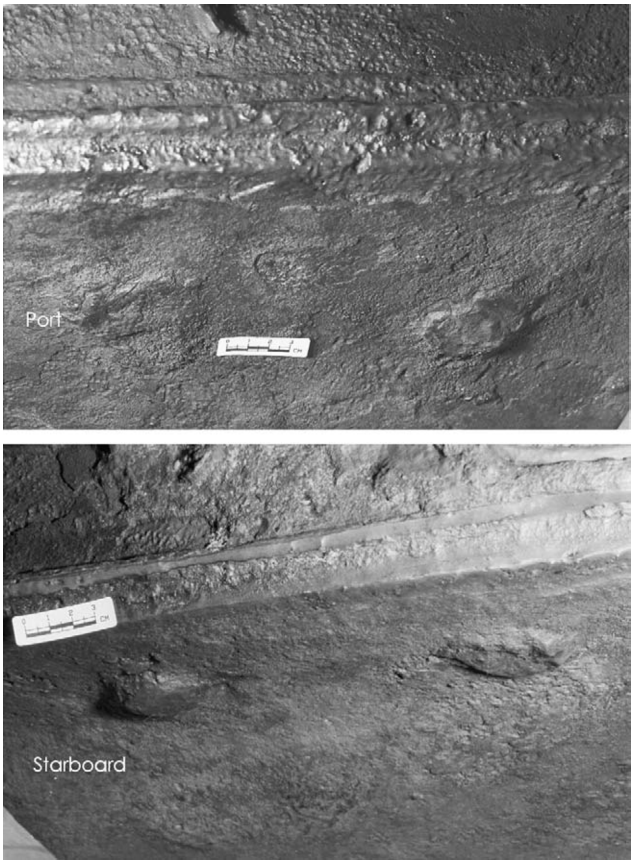


Fig. 7. The two pairs of bronze studs on the bottom plate. (Photograph by the author)

porosity levels when compared to other areas of the ram. Since the fins were the ‘cutting edges’ of the ram, it is tempting to relate the higher tin content and the low porosity in this area to an intentional effort to improve their mechanical properties. Improvement can be achieved by adding tin to the melt or by cold working. However, the low tin level (7.14%) noted in the second sample taken from the ramming head area (sample 1) is

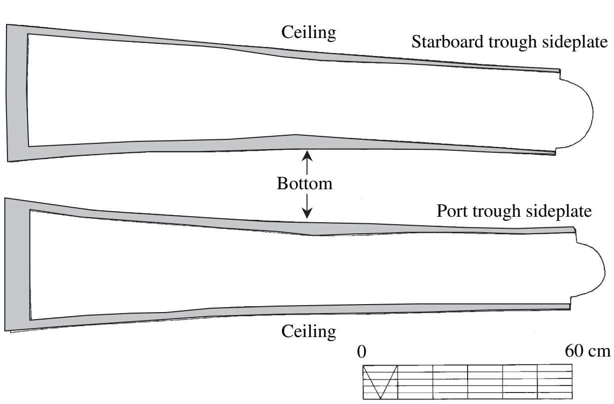


Fig. 8. Cowl ceiling and bottom plate wall thickness. The cross sections show the cowl ceilings and bottom plate wall thickness at their junction with the trough sideplates. (Drawing by A. Schreur and the author)

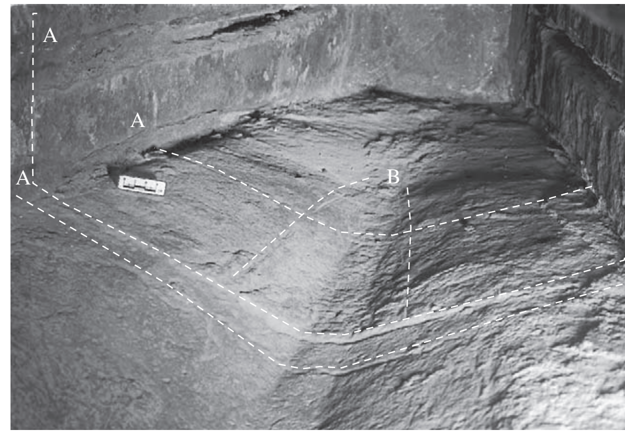


Fig. 9. The ram cavity viewed forward showing marks on the bottom plate and sides (dashed white line): *A*, traverse marks; *B*, oblique marks on the bottom plate. (Photograph by the author)

not consistent with this hypothesis, nor is the ‘as-cast’ dendritic structure evident in a metallographic cross-section taken from the upper fin. Based on available evidence, it appears that these compositional variations may be related to alloy segregation at the cast extremities, a characteristic occurrence in large casts that can lead to variations in alloy composition throughout an object [2:389–390,26]. This may also help to explain the high tin level in sample 9 (10.73%), which came from a protruding area on the ram main casting.

4. Previous studies: the sand-casting theory

The initial technical analysis of the Athlit ram undertaken by Eisenberg concluded that it was cast in a two-part sandbox, using a process often referred to as sand-casting [1,4:156–158,7:43–50, figs. 3-4, 3-6, 3-8,24: 141–146, pl. 20-1].

Eisenberg’s theory can be summarized as follows:

1. A model, or pattern, of the ram was made in wood.
2. The pattern was positioned horizontally on its side in the *drag* (the lower part of the sand-casting mould), and packed with sand up to the parting line. The *cope* (the upper part of the mould) was then positioned over the drag and packed with sand.
3. The sand-packed cope was lifted up to release the pattern. At this point, the area around the symbols was given a special clay coating to improve the surface quality during casting.
4. A wooden core coated with sand was placed inside the mould cavity. To control the wall thickness, the core was held at an even distance from the mould walls using rows of wooden spacers coated with clay and placed at 12 cm intervals.
5. The mould was closed and the bronze was poured into the mould.

Table 2
Chemical composition of metal samples from the Athlit ram obtained by ICP-AES

Sample No.	Site of Sample	Element (weight per cent)												
		Cu	Sn	Pb	As	Zn	Sb	Co	Ni	Fe	Ag	Au	Mn	Total
1	Bottom plate ridge under ram's head	90.8	7.14	<0.1	0.148	0.01	<0.05	0.082	0.030	0.039	0.009	<0.011	<0.001	98.3
2	Starboard trident handle device, main section	90.5	9.46	<0.1	0.212	0.02	0.016	0.068	0.032	0.041	0.013	<0.011	0.001	100.4
3	Cast on repair on starboard cowl tip	90.8	9.64	0.12	0.184	0.02	0.016	0.072	0.040	0.100	0.013	<0.011	<0.001	101.0
4	Port side helmet underside	90.1	9.89	<0.1	0.177	0.01	0.016	0.055	0.031	0.018	0.010	<0.011	<0.001	100.3
5	Inner side of section connecting cowl flanges	90.2	9.03	<0.1	0.185	0.01	0.011	0.058	0.032	0.017	0.011	<0.011	<0.001	99.6
6	[a]													
7	Cast on tailpiece repair, starboard edge aft of the join	90.1	10.32	<0.1	0.173	0.04	0.023	0.140	0.029	0.046	0.030	<0.011	<0.001	100.9
8	Cast on repair on port trough ear	87.1	11.11	0.14	0.180	0.11	0.021	0.072	0.040	0.082	0.015	<0.011	<0.001	98.8
9	Port trident handle device, main section	90.6	10.73	<0.1	0.190	0.10	0.013	0.067	0.031	0.050	0.012	<0.011	0.001	101.8
10	Starboard forward edge of top fin[b]	89.7	12.00	<0.1	0.218	0.15	0.022	0.083	0.034	0.121	0.014	<0.011	<0.001	102.4
11	Repair patch on the ramming head	94.3	9.31	<0.1	0.169	0.13	0.019	0.089	0.036	0.041	0.010	<0.011	<0.001	104.1

[a] Sample no. 6 was extracted 1 cm- to port of sample no. 5 for lead isotope analysis (work in progress).
[b] Sample no. 10 may have been contaminated as a result of the drill hitting a blow hole in the cast rich in powder-like black substance, most of which was discarded but some may have entered the sample.

It is evident, on observation of the ram, that the process by which it was cast differed substantially from that proposed by Eisenberg. The evenly distributed holes, interpreted by Eisenberg as the remains of wooden spacers used to hold the core, are in fact square chaplet holes, some of which still retain remnants of iron chaplets. Furthermore, the use of a two-part sand mould with a clearly defined parting line would most likely have resulted in a noticeable seam line: however, no indication of such a mark could be located by radiography or visually on the surface of the ram.

Finally the higher concentration of casting flaws at the aft section of the ram, combined with the low porosity of the ramming head, indicates a vertical orientation during casting, in which the pressure of the molten metal improves the quality of the cast in the lower portion of the mould. For the same reason, in later periods, bronze cannon were cast vertically with their breech down [3:259–260].

In order to accept the sand-casting theory, several problems must be addressed. How did the craftsman shape the core to reflect the exact dimensions of the bow? Could clay-coated wooden sticks support the heavy core without burning out, dislodging the core and destroying the cast? Finally, would the sand-casting technique offer any significant advantage that could not be achieved using the standard lost-wax technique common at this time? Eisenberg singled out the improved porosity of a sand-based mould and its better ability to expel gasses as the primary reasons for its adoption, arguing that a porous mould would have reduced the porosity of the casting, producing a sounder object. However, a wide range of Medieval and Renaissance technical accounts confirm the widespread use of clay-based moulds in the production of large cast bronzes [8: 363, 3: 234–260].

5. Interpreting the casting

Knowledge of Greek bronze casting practices is based primarily on the archaeological record. However, since the archaeological record is often incomplete, the interpretation of ancient bronzes is often aided by

Table 3
'Base' Composition of the Ram

Sample No.	Site of Sample	Element (weight per cent)												
		Cu	Sn	Pb	As	Zn	Sb	Co	Ni	Fe	Ag	Au	Mn	Total
2	Starboard trident handle device, main section	90.5	9.46	<0.1	0.212	0.02	0.016	0.068	0.032	0.041	0.013	<0.011	0.001	100.4
4	Port side helmet underside	90.1	9.89	<0.1	0.177	0.01	0.016	0.055	0.031	0.018	0.010	<0.011	<0.001	100.3
5	Inner side of section connecting o cowl flanges	90.2	9.03	<0.1	0.185	0.01	0.011	0.058	0.032	0.017	0.011	<0.011	<0.001	99.6
9	Port trident handle device, main section	90.6	10.73	<0.1	0.190	0.10	0.013	0.067	0.031	0.050	0.012	<0.011	0.001	101.8
	Mean values for ram based on samples 2, 4, 5, 9	**90.4**	**9.78**	**0.02**	**0.191**	**0.03**	**0.014**	**0.062**	**0.031**	**0.032**	**0.012**	**<0.011**	**0.000**	**100.5**
	Standard deviation	0.21	0.73	0.01	0.015	0.04	0.002	0.007	0.001	0.017	0.001			

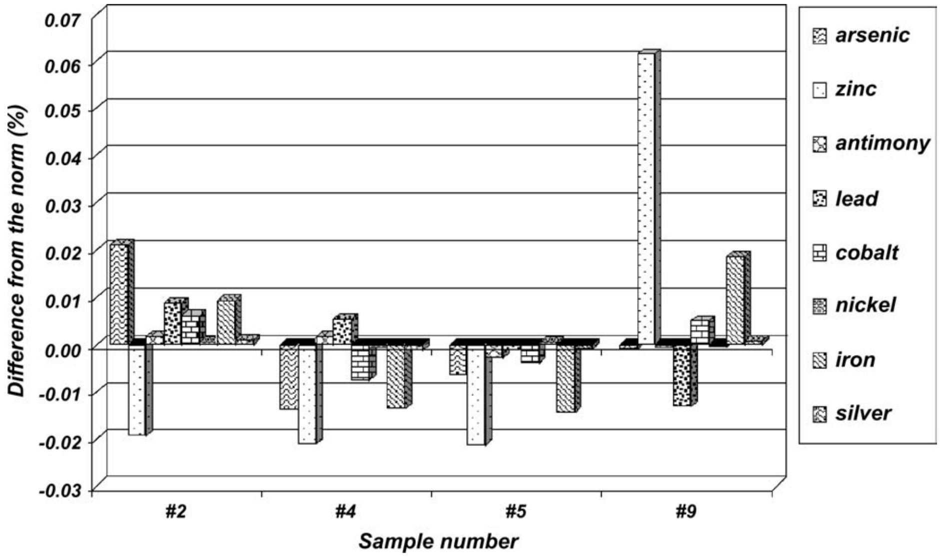


Fig. 10. Difference from the 'norm', analysis of trace elements in samples from the ram main cast.

studying accounts of Classical, Medieval, Renaissance, and modern authors addressing technical aspects of foundry practices. Taken as a whole, these point to the widespread use of the lost-wax casting technique as the principal method by which large and small bronzes were produced in ancient Greece.

The construction features, alloy composition and repairs observed in the Athlit ram in the current study share many similarities with other large cast Classical and Hellenistic bronzes. Altogether, this evidence suggests that the ram too was manufactured using the lost-wax casting technique.

Based on the close correlation between the Athlit ram and its bow timbers, Steffy suggested that the ram was made specifically for the bow of its ship. However, he did not venture into the technical aspects involved in achieving such a close match [28:38–39].

5.1. Hollow bronze casting by the lost-wax technique: the direct and indirect methods

The lost-wax technique is commonly divided into two main methods: direct and indirect.

In order to understand which casting method may have been used to cast the Athlit ram it is necessary to identify the main differences between the two processes, and how they may or may not fulfil the ram's design requirements, primarily its need to fit onto a designated bow.

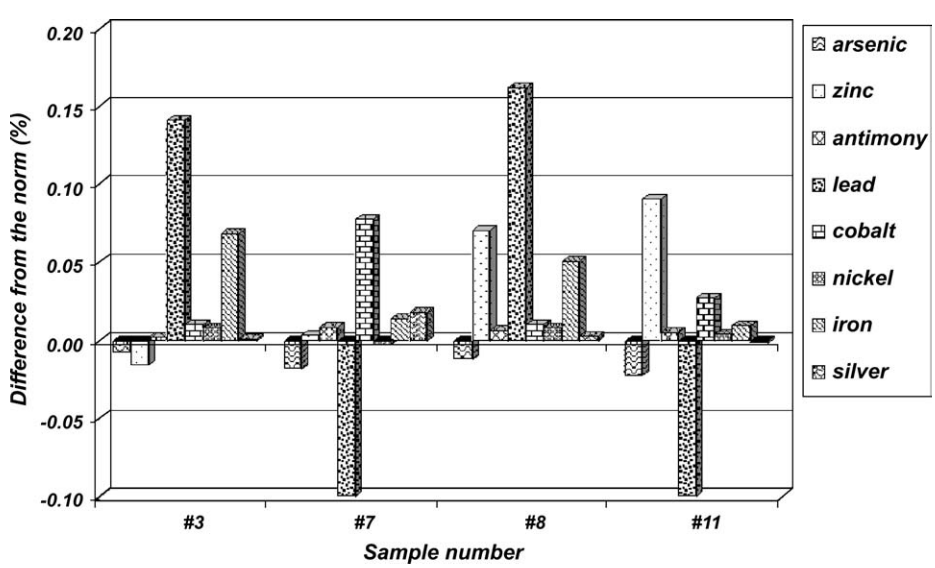


Fig. 11. Difference from the 'norm', analysis of trace elements in samples from repaired areas on the ram.

In the direct lost-wax method, a model is made of wax, and then invested directly in a clay mould that is subsequently baked in a casting-pit (a temporary casting installation dug below ground level) to harden the mould and melt the wax, hence the lost-wax method. The bronze is then poured into the empty space left in the mould. The direct lost-wax method allows the artist or bronze founder great freedom in the model design. However, since the model is destroyed in the casting process a new wax model has to be built for each and every new cast.

In the indirect lost-wax method, a model is made of wood, clay or any other suitable material. A multi-part mould is then built around the model. Once the mould is dry, it is opened to release the model. The mould is then reassembled and filled with wax to create an exact replica of the initial model. This secondary model, termed the 'inter-model' [32], is then invested and cast in the same manner as in the direct process.

To reduce production cost and increase structural stability, both casting methods often used a clay core introduced into the mould, thus producing a hollow bronze object.

The great advantage of the indirect method lies in its use of a multi-part reusable mould, which allows the bronze founder to create numerous wax models from a single master model. These inter-models can then be used to cast numerous identical bronzes. For this reason the indirect lost-wax casting method was widely used by Classical and Hellenistic bronze founders [12:35–38,18:789–790].

In order to produce a naval ram by the indirect method, the bronze founder had first to construct a model of the ram from which a negative was created, using a piece mould. By using this mould he could then produce identical wax inter-models, and thus cast numerous identical rams. Such mass-production of bronze rams would have been beneficial if the bows of ancient warships of a certain size class were consistent in their geometry and dimensions.

The study of ancient ships, however, suggests that hulls were seldom constructed perfectly, and that it would have been unreasonable to expect a shipwright to be able to make the complex timbers of a ship conform to an exact model. Significant variations in shape between one vessel and another were inevitable, even if built by the same shipwright. For example the hull of the fourth-century BC Kyrenia ship was asymmetrical due to the inability of its builder to fully control the shape of the hull (Steffy, 2000, personal communication). The same limitations most likely also applied to warships [28:32,29:61]. Archaeological evidence for the large variation in warship bows is evident in the 23 ram sockets preserved at the Octavian war memorial at Actium (30–29 BC). Murray hypothesized that the sockets represented rams taken from ships ranging in class from 'fives' to 'tens' [19:73–74, figs. 6.1–6-4, 20:35]. A comparison of the ram sockets within each one of these classes shows significant variations both in size and geometry. It appears that with inconsistent bow shapes each ram would have had to be custom-built to fit its designated bow. This key requirement could not be fulfilled by the indirect lost-wax method, which would have resulted in a series of identical bronze rams.

By contrast, the direct lost-wax method, by which each wax model is hand-built, deals with the reality of inconsistent bow shapes by allowing each ram to be custom-built to fit its designated bow. The craftsman could easily have built the wax model directly on its intended bow, using the latter as a temporary core. This sequence would have allowed a perfect match between the wax model, i.e. the ram to be, and its designated bow, with minimum effort, and would have obviated the need for pre-forming the large clay core. Once the wax model was completed and properly supported, it could be withdrawn from the bow, invested, cored and cast.

This modified form of the direct lost-wax process best explains many of the observations described so far, including the ram's intimate match to its bow timbers and the discrepancy in dimensions and design between starboard and port. The latter most likely reflects the free-hand modelling nature characteristic to the direct lost-wax process, and the craftsmen's attempts to accommodate the asymmetry in the bow. Other features observed in the ram casting, such as the uneven wall thickness and the flat underside of the decorative appendages, are also common characteristics of the direct lost-wax process, and thus fit well with the suggested use of the technique [22: f.n. 6].

Finally, this postulated construction sequence also offers an explanation for the lines found inside the Athlit ram cavity and the significant amount of pitch found between the bow timbers and the ram [28:32]. These construction marks, presumably the seam lines from the wax slabs used in some areas during the model construction, are commonly associated with the indirect lost-wax method, in which the clay core is introduced into the mould after the completion of the wax model, and therefore reproduces the texture of the wax surface with which it is in contact [22: f.n. 6,7]. However since the direct lost-wax process with a temporary core, proposed here, involves the introduction of the final clay core into the wax model after it is completed, in a sequence similar to that of the indirect process, it is anticipated that such construction marks would be preserved in a similar manner [9:46,12:66]. The application of pitch onto the bow timbers may have been the method used by the craftsmen to oversize the wax model in order to compensate for the shrinkage of bronze during the casting process. Oversizing the model would have allowed the final cast to fit snuggly onto the bow timbers.

6. Conclusion

Unlike most Classical and Hellenistic large-scale bronzes, which were normally constructed by the indirect lost-wax method, the current study suggests that the Athlit ram was most likely made by the direct lost-wax method. Furthermore, in contrast to the majority of large Classical and Hellenistic bronzes, which were assembled from separately cast sections, the Athlit ram was cast as a single unit.

To meet the ram design requirements and to cope with inconsistent bow shapes, it appears that the direct lost-wax method was modified by using the bow timbers as a temporary core on which the model was built. This newly described modelling technique can be termed 'hollow casting by the direct method with a temporary core'.

The following is a sequence postulated for the production of the Athlit ram.

1. The bow was coated with pitch to oversize the model and compensate for the shrinkage of the cast.
2. The model was then built on the coated bow with wax applied in a combination of slabs or paste, depending on the geometry and design requirements of the various sections of the ram.
3. Once the wax model was completed, the symbols were applied to the surface by a combination of freehand modelling and pre-formed wax shapes made in separate moulds.
4. The model was withdrawn from the bow and placed in a vertical position, head down, in the casting-pit.
5. A clay core was introduced into the ram's cavity and iron chaplets were driven into it through the wax walls.
6. The wax model was invested with a refractory clay mixture.
7. The mould was baked to remove the wax and the bronze was poured into the empty mould.
8. After the cast had cooled, the mould was broken and the ram was lifted out of the casting-pit using the lifting lugs.

The use of moulds to duplicate some of the symbols on the ram is a clear indication that the makers of the ram were familiar with the indirect lost-wax method and used it selectively when needed.

The intimate relationship between the Athlit ram and its bow reflects a close collaboration between bronze founders and shipwrights. Indeed, only through the combined effort of these two professions could a naval ram be successfully constructed. Furthermore, similarly to other bronzes of that time, which were cast in close proximity to their intended destination, rams were probably manufactured at the shipyard. This is further supported by the size, weight and design requirements of naval rams.

At present there are no parallel studies indicating the use of temporary cores in the manufacture of bronzes by the direct lost-wax method. It is hoped that the current study will draw attention to the possible use of this technique elsewhere. It is anticipated that further evidence for its use may be identified through the technical analysis of bronzes which were made to fit existing structures. This category may include bronze fittings for furniture, architectural elements, and machines of war.

Finally, it is hoped that the current research will encourage comprehensive study and technical analysis of other existing rams. Such work will undoubtedly yield a wealth of new and valuable information.

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