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ORIGINAL RESEARCH ARTICLE

# Copper-Based Sheathing and Fastenings for Wooden Ships: An Archeometallurgical Study of the Carron, Ancla Macuca, RMS *Forth*, and El Pesquero Wreck Sites Located in the Gulf of Mexico (Late 18$^{th}$ to Mid-19$^{th}$ Century)

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**Abstract**
One challenge in maritime archeology is correlating historical records, archeological findings, and material analysis data to accurately date and establish the provenance of shipwrecks. In the late 18th and early 19th centuries, European naval construction emphasized improvements to the durability of wooden ships, especially for tropical waters. The introduction of metal sheathing was a significant innovation to safeguard ship hulls against wood-boring organisms. Archeometallurgical analysis of copper-based sheathing and fastenings provides crucial insights into shipwreck technology and construction context. This study examines copper sheathing and fastenings on wooden ships from the late 18th to mid-19th century, focusing on wrecks in the Gulf of Mexico. Artifact analysis from these sites sheds light on evolving shipbuilding practices during the early industrial period. Additionally, archeometallurgical analysis has provided chronological references that assist in identifying these wrecks, particularly given the absence of ship hulls, which have degraded under tropical marine conditions.

**Keywords** Archeometallurgy · Nautical technology · 18$^{th}$ and 19$^{th}$ Century · Shipwrecks

## Introduction

During the late 18th and early 19th centuries, maritime activities in the Gulf of Mexico, the Antilles, and the Caribbean were diverse, driven by commerce, resource exploitation, and military conflicts. Evidence of these activities can be found in historical records and archeological remains, particularly shipwrecks, which offer valuable insights into the region's nautical activities. European vessels played a crucial role in this maritime pursuit. During this period, wooden vessels underwent

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significant improvements, with copper sheathing technology standing out as a key advancement. Initially implemented to protect wooden hulls from damage by marine organisms, copper sheathing notably enhanced both the speed and durability of vessels. However, its introduction presented challenges, particularly the accelerated corrosion of iron fastenings due to galvanic reactions with the copper sheathing. The British Royal Navy addressed this issue by experimenting with copper alloys and eventually adopted "hardened" copper bolts for use below the waterline, a practice later adopted by other European navies.

The transfer of copper sheathing technology from Great Britain to France, Spain, and beyond was a result of both industrial espionage and technological exchange. This technology spread further, extending to merchant vessels, particularly through the British East India Company. By the mid-19th century, advancements in copper alloys, such as Muntz metal, enhanced the efficiency and cost-effectiveness of sheathing and fastenings for vessels (1–8).

## Brief Overview of Selected Archeological Sites

### Carron Site, Cayo Nuevo

This wreck site is located northeast of Cayo Nuevo Reef on a limestone bed at a depth ranging from 5 to 7.9 m (Fig. 1). Scattered metallic sheets, concentrated primarily on the southern end, are found alongside other diagnostic remains, including 43 iron guns, 5 anchors, musket balls, lead fragments, and iron rudder hinges. Notably, one gun is inscribed with the foundry name (*CARRON*) and the manufacture date (*1775*) on its trunnion face (9). The use of copper-alloy sheathing, bolts, and sheathing tacks suggests a *terminus post quem* for the wreck events of about the early 19th century (10–13).

Moreover, two 16th-century artifacts—a bronze demi-culverin (dated 1552) and an anchor—were discovered nearby (9, 10, 12). The broad time range of the identified objects suggests a palimpsest, indicating that the remains of at least two wrecks are likely presented. Analysis of copper-alloy fastenings may provide insights for the contextual assessment of sites.

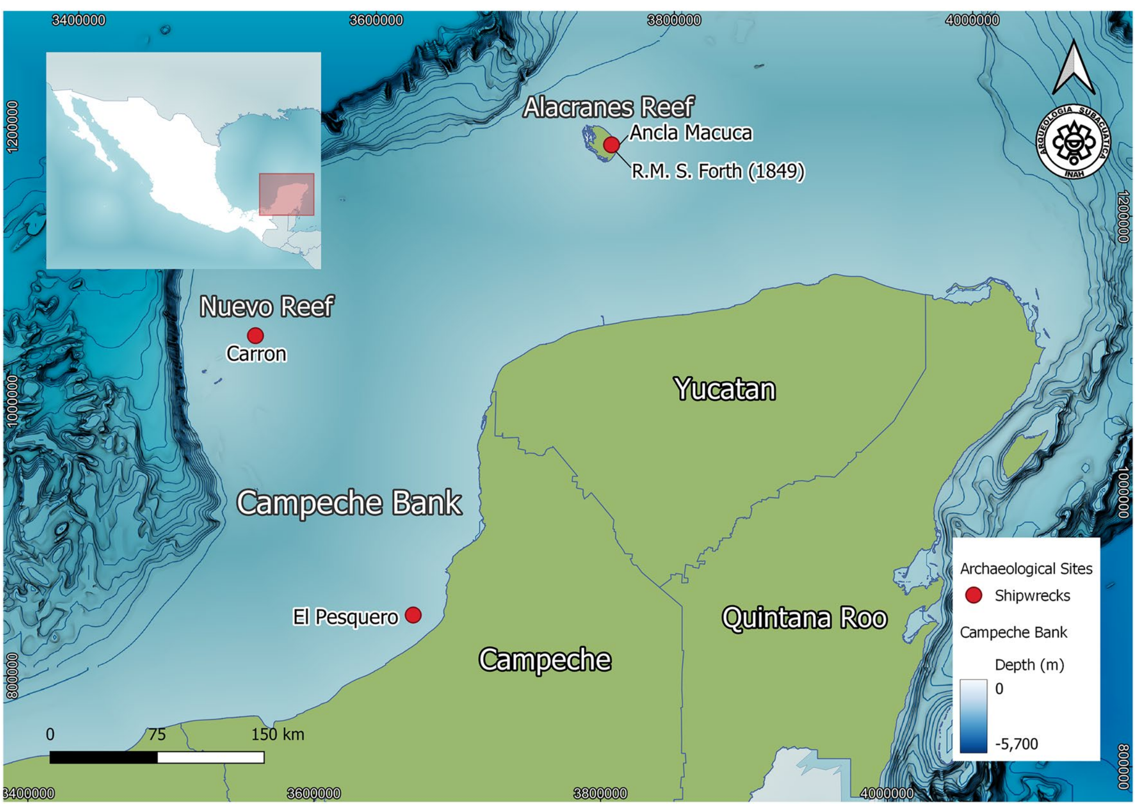



**Fig. 1** Map depicting the locations of the Ancla Macuca, RMS *Forth* (1849), Carron, and El Pesquero shipwrecks. Also shown are the position of Campeche Sound in the southeastern region of Mexico, along with the locations of PNAA, Cayo Nuevo, and the Campeche Coast. ©SAS-YUC Archive, INAH (2023). Credit: Ma. Fernanda Ramírez Islas

### Ancla Macuca and RMS *Forth* (1849) Sites, National Park Alacranes Reef

Natural site formation processes have resulted in an overlap of these shipwreck remains, creating a palimpsest (13) (Fig. 1). Materials associated with both vessels, including copper-based sheets and fastenings, present technical similarities, complicating their identification and association with a particular vessel. The Ancla Macuca site, likely a merchant vessel from the late 18th century, yielded a remarkable assemblage of artifacts, including 236 gold jewels (23-carat), emeralds, diamonds, silver macuquina coins (1620–1650), and six iron guns (13–15).

The wreck of RMS *Forth* (1849) revealed structural remains, including the steam propulsion system. Historical records indicate that it belonged to a fleet of 14 steamers from the Royal Mail Steam Packet Company, which was regularly engaged in a transoceanic mail route. Built in 1841, the ship's hull was constructed of oak and teak and equipped with a 450 HP side-lever single steam engine (10, 13, 16).

### El Pesquero Site, Champotón

This site covers approximately 900 $m^2$, with remains embedded in a coral formation measuring about 14 m in length and oriented east–west (Fig. 1). Due to the tropical marine environment, only limited portions of the wooden hull have survived. The assemblage includes an iron stove, bricks (likely from the ship's kitchen), six guns ranging from 3 to 9 pounds, round shot, pig iron, and shingle ballast. Sheathing tacks, a spike, and fragments of lead were also recovered. A highly corroded sheet containing tacks was discovered positioned parallel to the area with the greatest concentration of archeological remains (Fig. 6).

Eighty meters north of the main assemblage, an anchor was located, though its association with the site remains undetermined. These materials, particularly the copper-alloy fastenings, could offer insights into the ship's construction and potential trade networks (12, 17, 18).

## Methodology

A historiographic review of the production cycle of copper sheathing and fastenings used in shipbuilding was conducted and compared with the archeological data gathered from the selected sites. In addition, characterization studies were performed on samples of sheeting, sheathing tacks, nails, and bolts samples from these sites (11). (Samples were labeled with an acronym of the archeological site and a number (e.g., SASY, AM, PI).) Photogrammetry and 3D modeling were employed to record the shape and dimensions of the objects. X-ray imaging was employed to analyze metallic remains in severely deteriorated sheathing.

The metallographic examination of copper-based samples to determine microstructural features was conducted using light microscopy (LM) and scanning electron microscopy (SEM). Additionally, semi-quantitative elemental composition analysis was performed through energy-dispersive x-ray spectroscopy (EDX) and x-ray fluorescence (XRF). The samples were embedded in thermoplastic resin, then ground and polished to achieve a specular surface. To reveal the microstructure, a hydroalcoholic solution of ferric chloride was applied. For brass samples, the areas unaffected by selective corrosion (dezincification) were selected.

Vickers microhardness testing was conducted on polished sections of the samples to evaluate their mechanical properties (Hardness, 1999). A load of HV 0.2 was applied to each sample for 10 seconds. This measurement was performed using a Duramin-40 microhardness tester from Struers®. These data provided insights into the manufacturing techniques employed, such as cold working and annealing.

## Results and Discussion. Metallurgical Analysis and Findings

### Carron

At the Carron wreck site, two types of brass bolts were identified, both shared a similar composition but exhibited differences in shape and microstructure (Fig. 2). Bolt SASY016 is characterized by a partially recrystallized structure with grains displaying a high level of corrosion (Figure 2a, b, c). Elongated metallic inclusions in the longitudinal direction suggest that the bolt was manufactured through plastic deformation, likely by hot (or possibly cold) forging, followed by annealing. Slip bands near the surface suggest slight cold working. The alloy composition is 65% Cu and 35% Zn, with trace amounts of Pb and Fe. In contrast, bolts SASY015 feature a wedge-shaped tip and display a Widmanstätten-type grain structure, likely a result of rapid cooling after the hot deformation process (Figure 2d, e, f).

According to the Cu-Zn phase diagram, the α phase precipitates from the single-phase ß during cooling, forming α laminations within a ß matrix (19). (For duplex brasses, the α phase is a solid solution of Zn in Cu, crystallizing in a face-centered cubic (FCC) structure and readily deformable in cold working. The ß phase is an intermetallic compound with an approximate 1:1 composition ratio. The ß phase forms once the α phase reaches saturation and crystallizes in a body-centered cubic (BCC) structure (19).) The different microstructures of the bolts suggest at least these two possibilities: a) they were manufactured for different purposes,

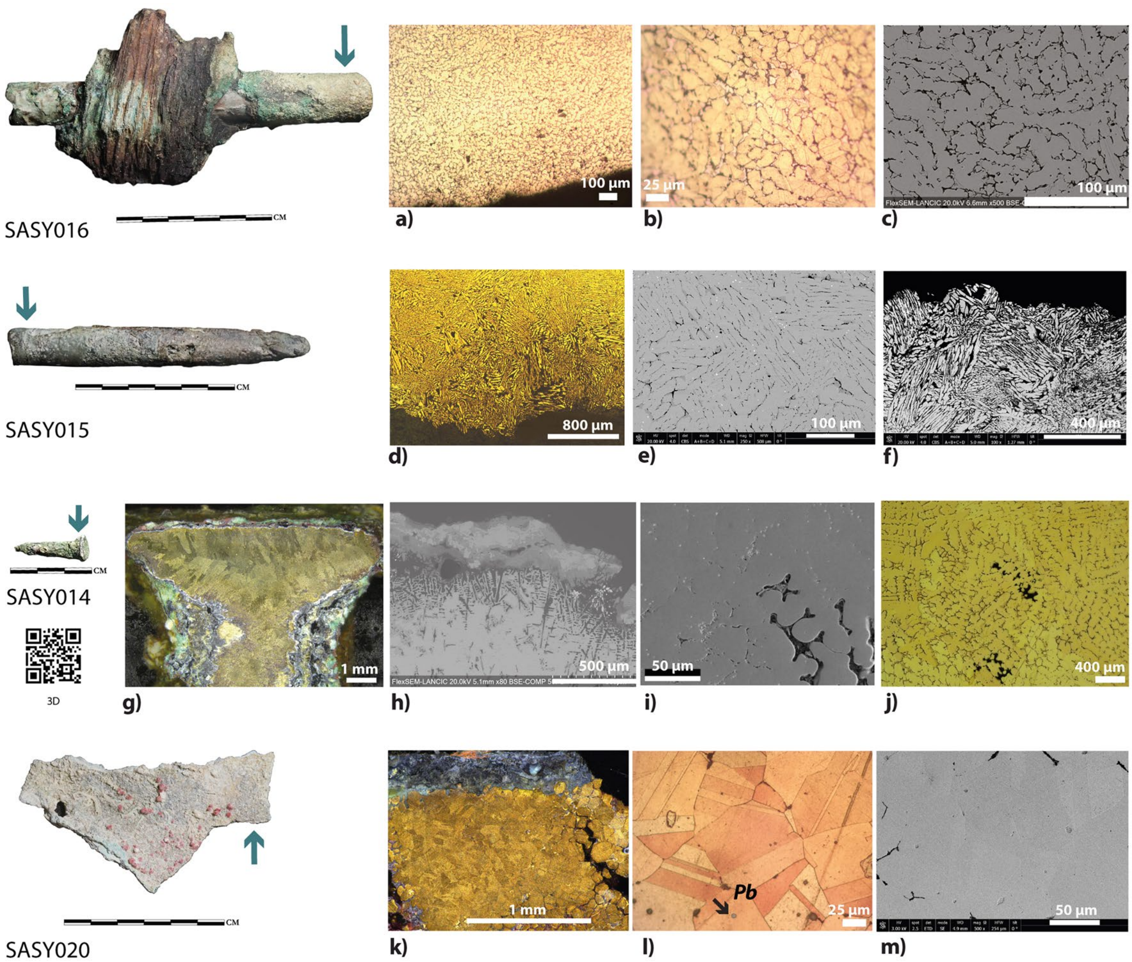



**Fig. 2** Carron site. The image shows bolts SASY015 and SASY016, sheathing tack SASY014, and sheet SASY020, along with the photomicrographs displaying their microstructure (LM and SEM). The arrow indicates the sample area. **a**–**c** Cross sections: **a** Partially recrystallized structure with a high degree of dezincification, etched; **b**, **c** Higher magnification views. **d**, **e**, **f** Cross section and edge portion (LM without etching and SEM), showing a Widmanstätten-type grain structure. **g**–**j** Cross section of the head: **g**, **j** LM, showing α and β phases in the dendritic microstructure, etched; **g** arrows indicates the presence of two phases; **h**, **i** SEM, with **i** showing a higher magnification of the interdendritic space. **k**–**m** Equiaxed grains with recrystallization twins: **k**, **l** LM, Etching: hydroalcoholic ferric chloride; **m** SEM

such as securing distinct parts of the hull, and b) they were produced in different workshops using different methods. Similar microstructural variations in brass have also been documented by Bram and colleagues in the Akko Tower wreck (20, 21).

Sheathing tack SASY014 exhibits a dendritic microstructure, with larger grains concentrated at the head where solidification was slower (Figure 2g, h, i, j). These characteristics are typical of casting and solidification without subsequent thermomechanical treatment. The alloy consists primarily of Cu (65.9%) and Zn (33.7%), with minor Pb content (0.2%) precipitating in the interdendritic regions.

The microstructure of sheet SASY020 displays equiaxed grains of various sizes (20-200 µm) with recrystallization twins, indicating that the sheet was manufactured by rolling, either hot or cold, followed by annealing (Fig. 2k, l, m). The sheet is made of brass and features elongated Pb inclusions in the direction of hammering or rolling. The brass alloys documented at the site resemble the composition of Muntz metal (about 60% Cu – 40% Zn), patented in 1832 (8, 22–26).

## Ancla Macuca and RMS *Forth* (1849)

At Alacranes Reef, the correlation between historical records and archeological remains enabled the identification of one shipwreck—the RMS *Forth*, a steamship that sank in 1849. In contrast, the archeological remains of the Ancla Macuca wreck suggest that this second vessel might date to the second half of the eighteenth century.

Analysis of copper-based fastenings and sheets at this location revealed two distinct compositional groups: one of unalloyed copper (Fig. 3) and the other consisting of brass and bronze alloys (Fig. 4-5).

The use of brass in shipbuilding began in the early nineteenth century, with applications including bolts, nails, and sheathing (1, 8, 25, 26). Consequently, the brass remains were associated with the RMS *Forth* (1849). In contrast, the unalloyed copper elements, introduced into the European shipbuilding practices in the last third of the eighteenth century, may correspond to the Ancla Macuca wreck. However, this does not exclude the possibility that some components of unalloyed copper might also belong to the British steamship, as a single vessel could incorporate materials from different periods and origins (10). Additionally, the prolonged use of unalloyed copper in certain naval contexts must be considered.

From the Ancla Macuca site, bolt AM063 exhibits a microstructure of equiaxed grains of unalloyed copper of variable grain sizes (10-100 µm) and recrystallization twins (Fig. 3a, b, c). In the longitudinal section, the grains are elongated (Fig. 3a). This bolt was likely produced by plastic deformation, probably through hot forging. The presence of deformation lines and elongated grains at one end of the bolt suggests hammering, possibly occurring during the vessel's construction.

Sheathing sheet PI07 is also composed of unalloyed copper (Fig. 3d-h). Its microstructure displays equiaxed grains, recrystallization twins, and metallic inclusions (Pb, As, Bi), elongated along the manufacturing direction (Fig. 3f, g). This evidence indicates that the sheet was produced by rolling, potentially either hot or cold, followed by annealing. They, while somewhat aligned, vary in thickness and length. This feature suggests that the sheet may have been further shaped by hammering. If the vessel is of Spanish origin, as suggested by contextual evidence, historical information raises several considerations (14, 15). Copper sheathing was first introduced in Spain in 1782, but no rolling mill was established there until 1790 (10, 27). Therefore, it is plausible that the vessel was sheathed in the late eighteenth century. However, given the presence of clandestine activities in the Gulf of Mexico, it is also conceivable that the vessel was of English origin, operating in the Campeche Sound. If so, it may date to an earlier period, as the British merchant fleet began adopting copper sheathing for hulls in the last third of the eighteenth century (28, 29).

At the RMS *Forth* (1849) site, sheet AM084 is composed of brass with 62-66% Cu and 38-34% Zn. Its microstructure

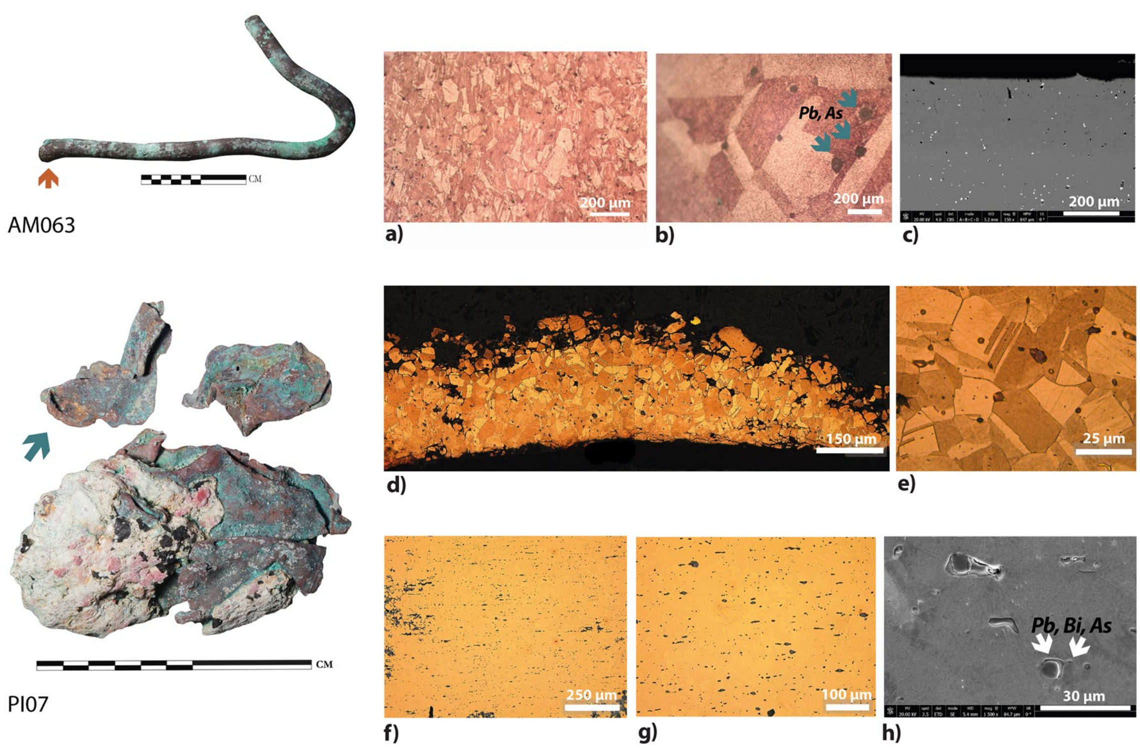



**Fig. 3** Ancla Macuca site. Equiaxed grains of unalloyed copper of bolt AM063: **a** Longitudinal section (LS), viewed under LM, etched; **b** Cross sections (CS), viewed under LM, etched; **c** CS, SEM. Unalloyed sheathing sheet PI07: **d**, **e** CS under LM, etched. **f**, **g** Metallic inclusion (Pb, As, Bi) elongated following the manufacturing direction, longitudinal section (LS), non-etched. **h** SEM view. Etching: hydroalcoholic ferric chloride. The arrow indicates the sample area.

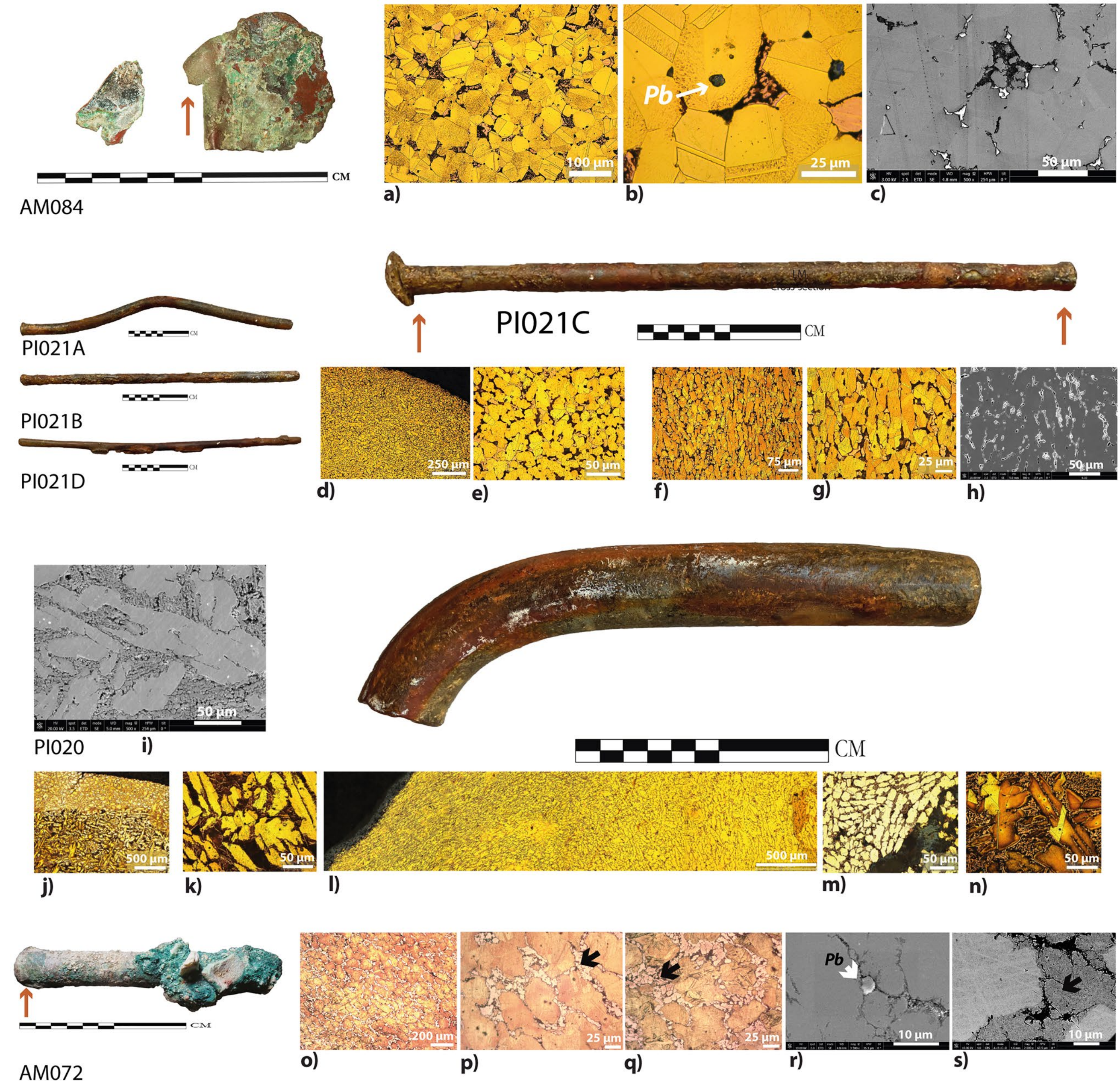



**Fig. 4** RMS *Forth* (1849) site. Equiaxed grains of brass in sheathing sheet AM084: **a**, **b** Cross sections (CS) under LM, etched; **c** SEM image. Brass bolt PI021C: **d**, **e** CS under LM, etched; **f**, **g**, **h** Longitudinal section (LS) showing elongated grains; **f**, **g** LM, etched; **h** SEM, non-etched. Brass bolt PI020: **i** CS, SEM view; **j**, **k** CS, LM, etched; **l**, **m**, **n** LS, LM, etched. Brass bolt AM072 (black arrow indicates dezincification area): **o** LS, LM, etched, showing elongated grains; **p** higher magnification center; **q** same magnification border; **r** SEM showing Pb inclusions at grain boundaries; **s** SEM showing higher magnification of the dezincification process. Etching: hydroalcoholic ferric chloride. The arrow indicates the sample area

consists of equiaxed grains of various sizes (40-300 µm) and recrystallization twins (Fig. 4a, b, c). The sheet also contains metallic inclusions of Pb with minor amounts of Bi, As, and Fe and non-metallic of S. These data, along with the alignment of the inclusions, suggest that the sheet was manufactured by rolling—either hot or cold, with annealing in the latter case (Fig. 4a, b, c).

For the bolts, the composition is consistent with Muntz brass. Bolts PI021 A, B, C, and d show an average composition of Cu 64%, and Zn 35%, with traces of Pb, Mn, and Fe. Brass bolts AM072 (63-65% Cu – 37-35% Zn), PI021C (66% Cu – 34% Zn, with traces of Fe), and PI020 (67% Cu – 33% Zn) share similar compositions (Fig. 4). In cross section, bolts PI021C (Fig. 4d, e) and PI020 (Fig. 4i, j, k) exhibit a microstructure of equiaxed grains of varying sizes and recrystallization bands, indicative of plastic deformation in the manufacturing process. Slip bands along the surface likely resulted from cold working in the final production stage. In the cross section of bolt PI020, a peripheral zone with smaller grains indicates intense deformation and partial recrystallization during the final production stage (Fig. 4j). In the longitudinal section, the grains are elongated, likely due to plastic deformation in the manufacturing process (Fig. 4l, m). This bolt also displays significant dezincification, resulting from selective Zn dissolution in the marine environment (Fig. 4n). (Zinc dissolution occurred along the grain boundaries of the brass microstructure, in some instances penetrating to the core of the metal (Fig. 4m).)

The square-bodied nails, like the bolts and sheets, can be grouped based on composition. Of the four square-bodied nails (PI016 A, B, E and PI022A) (Fig. 5), PI016A and B exhibit similar dendritic microstructures and ternary bronze compositions (85-89% Cu, 6-7% Zn, and 3-4% Sn, with traces of Fe), and numerous pores in the matrix (Fig. 5a-f). Nail PI016E shows advanced intergranular corrosion, with marine environment minerals filling its pores (Fig. 5k-m). Its originally dendritic microstructure is partially recrystallized, and its composition (82% Cu, 6% Zn, 6.8% Sn, and 3.3% Pb) differs slightly from the others. The microstructural characteristics suggest potential heat exposure, either during manufacturing (e.g., annealing) or as a result of the vessel's sinking. The fourth square-bodied nail (PI022A) is in an advanced state of corrosion, yet still retains a visible dendritic with a slightly different composition (62-66% Cu, 30-33% Zn, 1-3% Sn, and traces of Pb) (Fig. 5g-j).

At this site, three sheathing tacks (PI016C, PI016D and AM052) were analyzed, displaying a composition consistent with quaternary bronze. The average composition of these tacks is 77-87% Cu, 6-11% Zn, 4-7% Sn, and 3-6% Pb, with traces of Fe (Fig. 5n-w).

The dendrites within the tacks have an approximate composition of 82% Cu, 10% Zn, 5% Sn, and 2% As. In the interdendritic regions, the Sn percentage increases to 23% (Fig. 5m, p). Below 320°C, copper and tin exhibit limited mutual solubility, leading to precipitation in these areas. The elevated Sn concentration is attributed to segregation during solidification (Fig. 5r). Lead inclusions, mostly containing traces of As, Ni, and Fe, are observed; as Pb is practically insoluble in copper alloys, it segregates and precipitates within shrinkage voids during solidification (19) (Fig. 5s, u, v).

Pb concentration increases from the tip to the head of the nail, correlating with the cooling pattern of the alloy, as the head is oriented upward in the mold. Micro-shrinkage occurs due to the contraction of the metal across the nail head during cooling (Fig. 5t, w). Elemental mapping using EDX confirmed that areas with Pb also contain S and As (Fig. 5m, p). SEM imaging revealed a dark phase in the form of angular particles in the peripheral areas of the Pb inclusions or scattered within the alloy's microstructure (Fig. 5u). These particles primarily consist of Zn (62%), S (23%), Cu (14%), and Sn (1%). The presence of As impurities likely reflects the ore source and limitations in refining technology of the period (30).

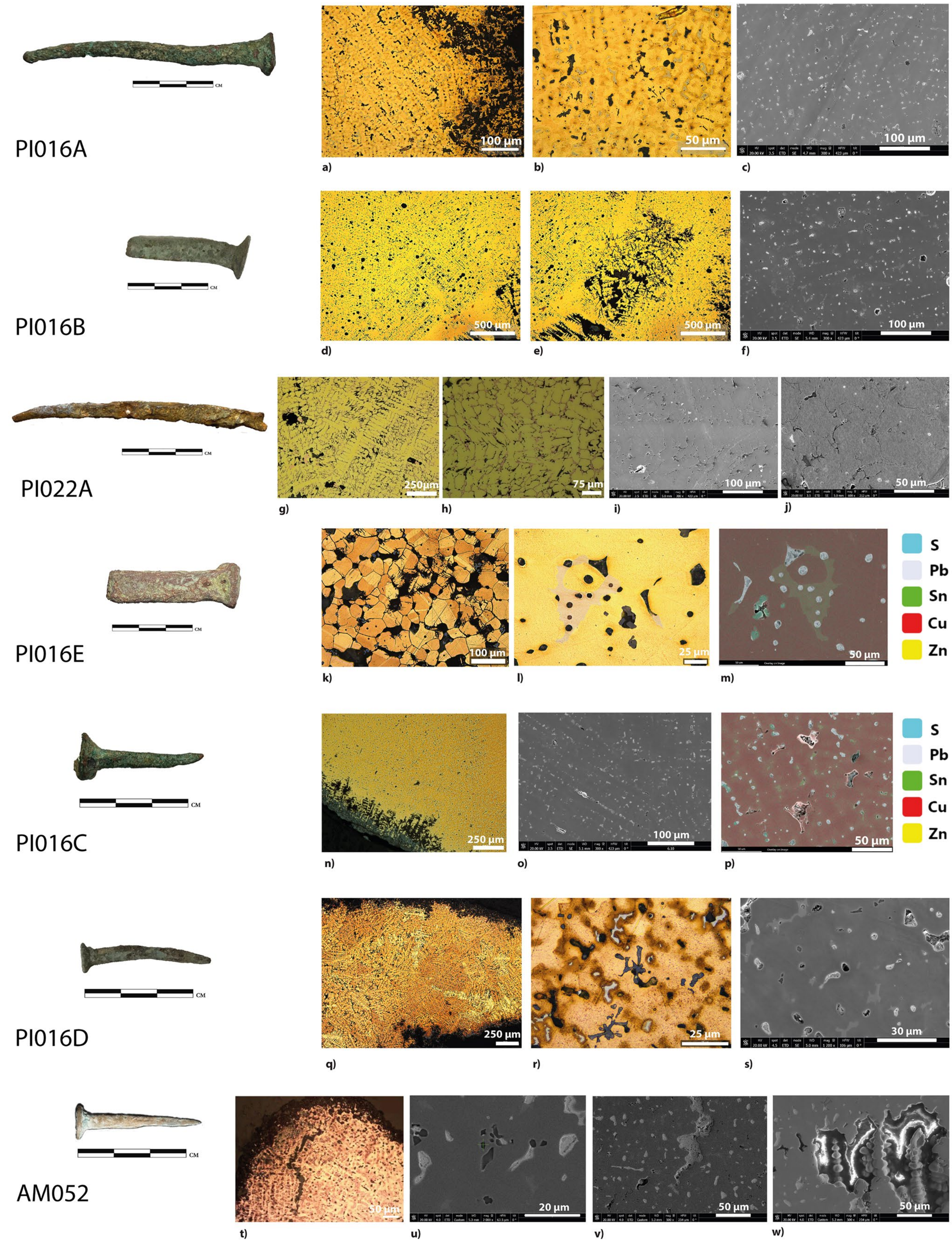
## El Pesquero

At El Pesquero site, a thin and highly deteriorated sheet —containing three nails embedded within the corrosion products—was recovered (PQ060) (Fig. 6). X-ray analysis revealed a retained metallic matrix within a concretion, which was carefully removed (PQ060D) (Fig. 6a, b). SEM-EDS and metallographic studies determined that the sheet's composition is predominantly copper (99-100%), with localized inclusions of Bi and As. Its microstructure displays equiaxed grains with deformation twins (Fig. 6a, b).

Three sheathing tacks, PQ060 A, B, and C, attached to the corroded sheet PQ060, were made of a quaternary brass (88-90.5% Cu, 3-4% Zn, Sn 1-4.5% Sn, and 2.5-3.5% Pb, with traces of Fe and As) and exhibit a dendritic and biphasic microstructure, indicative of a casting process (Fig. 6c-n). Micro-shrinkages formed during solidification are evident in the head area, and carbon particles were detected in two of the tacks (Fig. 6e). As expected, Pb precipitated within the interdendritic spaces (Fig. 6f, i, m, r).

An additional sheathing tack, PQ020, was found isolated approximately five meters apart from the main concentration of archeological remains. It is composed of a quaternary bronze, similar to the other artifacts (91-92% Cu, 4-5% Sn, 2-5% Zn, and 1% Pb), but lacks traces of Fe or As (Fig. 6o-r). The slight compositional differences are likely attributable to the inherent heterogeneity of such artifacts, exacerbated by alterations induced by corrosion processes. This tack also displayed dendritic microstructure as cast. All sheathing tacks displayed segregation of a Zn-rich phase within the interdendritic spaces, with a compositional gradient correlated with variations in hardness. The PQ020 tack exhibited slip bands, more pronounced at the tip than in the body and head, likely due to cold working. Whether this feature results from manufacturing or subsequent use is difficult to determine. During the vessel's sinking, fastenings in the ship's structure might have experienced differential stresses depending on their location and hull integrity.

The square-bodied nail PQ044 is composed of a quaternary bronze, primarily Cu (89-91%), with smaller percentages of Zn (3-4%), Sn (3-4%), Pb (1-3%), and traces of Fe. It displays a dendritic microstructure indicative of a casting process (Fig. 6s, t, u). The nail's composition closely aligns with that of the analyzed sheathing tacks. The compositional analysis of the sheets, sheathing tacks, and nails, and their


PI016A
100 µm
50 µm
100 µm
a)
b)
c)
PI016B
500 µm
500 µm
100 µm
d)
e)
f)
PI022A
250µm
75 µm
100 µm
50 µm
g)
h)
i)
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◂**Fig. 5** RMS *Forth* (1849) site. Nails (PI016 A, B, E, PI022A) and sheathing tack (PI016 C, D, AM052). PI016A: **a**, **b** Cross sections (CS) viewed under LM, etched; **c** CS under SEM, non-etched. PI016B: **d**, **e** CS under LM, etched; **f** CS under SEM, non-etched. PI022A: **g** CS under LM, non-etched; **h** Longitudinal section (LS) under LM, non-etched; **i** LS under SEM, non-etched; **j** CS under SEM, non-etched. Partially recrystallized grains of nail PI016E: **k**, **l** CS under LM; **k** etched; **l** higher magnification, non-etched; **m** SEM, non-etched, same area as (l), EDS map. PI016C: (n) CS under LM, non-etched; **o** CS under SEM, non-etched; **p** CS, higher magnification under SEM, EDS map. PI016D: **q** CS under LM, etched; **r** CS under LM, etched, higher magnification; **s** CS under SEM, non-etched. AM052: **t** CS under LM, etched; **u** CS under SEM, non-etched; **v** CS under SEM, non-etched, micro-shrinkage filled with Pb; **w** CS under SEM, non-etched, dendrites in micro-shrinkage space. Etching: hydroalcoholic ferric chloride

correlation with other site remains, suggest that this vessel dates from the late 18th to early 19th century.

### Influence of Metallurgical Processes on Microhardness

The microhardness of the studied alloys varies notably based on both metallurgical processing and alloy composition, offering insights into the behavior and durability of the artifacts. In brass bolts, for instance, the differences in microstructure between SASY015 (Longitudinal hardness (LH): 110.17 HV – Transverse hardness (TH): 126.58 HV) and SASY016 (LH: 144.27 HV – TH: 148.4 HV) illustrate the impact of distinct manufacturing processes on hardness. These variations are critical for understanding the functionality of these bolts within shipbuilding, where hardness influences the durability and mechanical strength of fasteners.

Similarly, the dendritic microstructure of sheathing tacks and nails, such as SASY014 (LH: 132 HV – TH: 172.5 HV) and PQ060A (LH: 143.5 HV – TH: 118.4 HV), indicates that the solidification without subsequent thermomechanical treatments results in heterogeneous microhardness. In particular, the segregation of Pb in interdendritic spaces and the precipitation of Zn-rich phases create localized areas of lower hardness, which could adversely affect the structural strength of these components.

Cold working, as observed in brass sheets and bolts [SASY-020 (LH: 103.5 HV – TH: 123.3 HV), PI-020 (LH: 140 HV – TH: 149 HV)], increases hardness by inducing slip bands, which enhance material strength. Recrystallization, conversely, restores ductility in cold-worked bronze, although it decreases hardness compared to material worked without annealing.

In summary, the microhardness of the studied materials is directly related to the metallurgical techniques employed, such as casting, forging, and rolling. Copper and its alloys show variabilities in hardness due to elemental segregation as well as cold or hot working processes.

## Conclusions

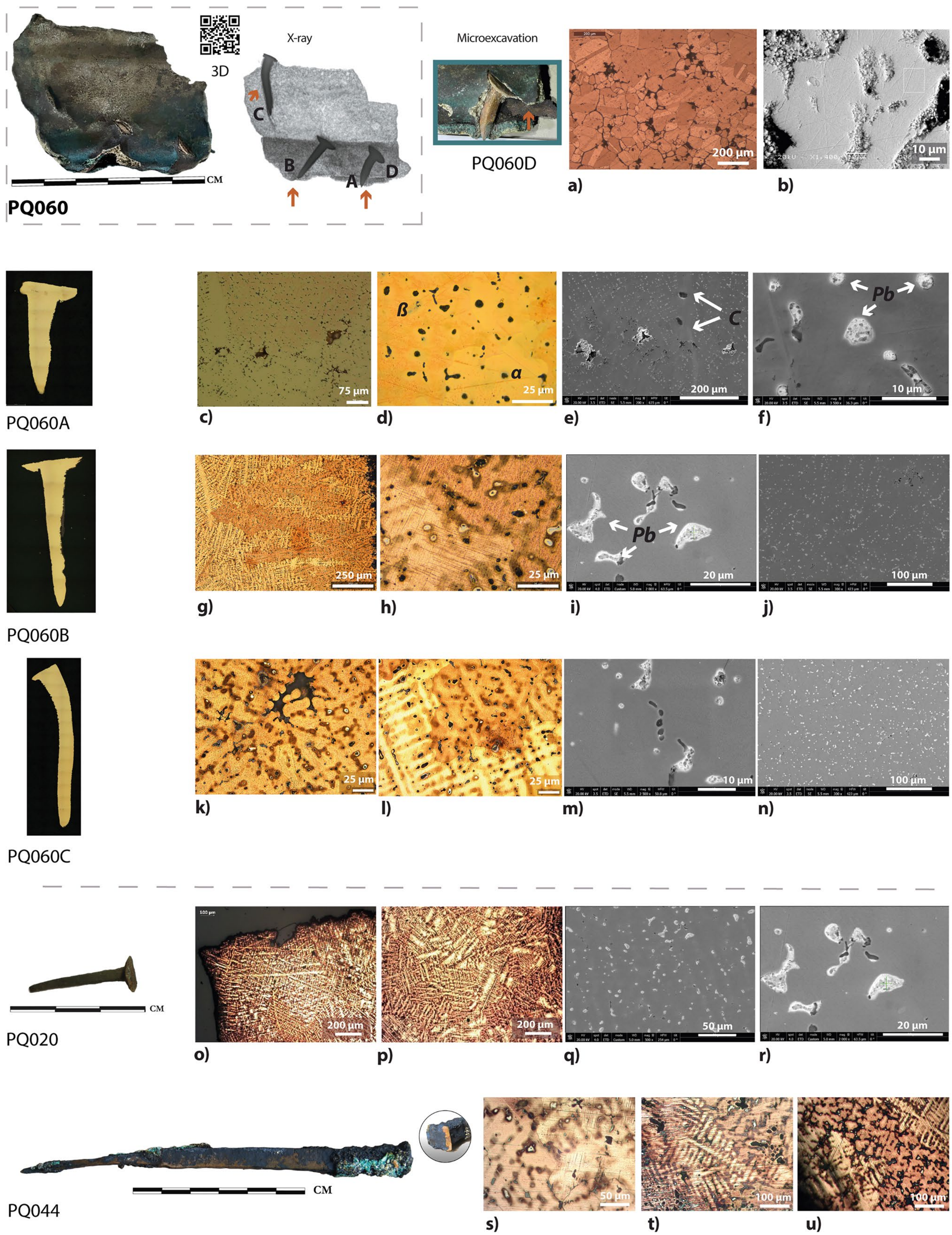
This research contributes on two levels: first, by providing specific microstructural and compositional data for the sheathing and fastenings used in different vessels, and second, by offering broader insights into the formation processes and identification of the wreck sites.

The archeometallurgical analysis of copper and copper-alloy sheathing, sheathing tacks, nails, and bolts from shipwrecks located in the Campeche Bank has revealed several key technological features: a) composition, b) manufacture, c) use, and d) deterioration processes. These findings contribute to a more nuanced understanding of the materials used for shipbuilding during the late 18th to mid-19th centuries.

The development and adoption of copper sheathing varied across European nations during the last third of the 18th century. Our findings are significant for maritime archeology in the Gulf of Mexico, particularly for assessing unidentified wreck sites. However, to address the origin or nationality of the vessels, additional historical research and further analysis of archeological remains are required.

This research also enabled a detailed examination of the palimpsest formed by the wrecks of the Ancla Macuca (ca. late 18th century) and RMS *Forth* (1849). The metallurgical analyses provided valuable data for correlating the composition of the fastenings and sheathing remains with a specific period, serving as a reference frame for the metals used in shipbuilding. Another example of palimpsest is the Carron site, which contains archeological evidence ranging from the 16th-century bronze demi-culverin to 18th-century iron guns (one, dated from 1775) and a brass sheathing and fastenings. This suggests that the site may represent at least two different shipwrecks occupying the same area. An alternative interpretation considers that the site could correspond to a 19th-century vessel transporting earlier materials, similar to the Spanish frigate *Nuestra Señora de las Mercedes*, built in 1788 and sunk in 1804, whose cargo included bronze guns from the late 16th and early 17th centuries (31). Both general and specific aspects of the methodology employed in this study could be applied to other shipwrecks from the same period.

In summary, this study underscores the value of integrating metallurgical analysis with historical and archeological evidence from shipwrecks to study metals used in wooden shipbuilding. This integrated approach not only enhances our understanding of the materials and techniques employed but also highlights the broader historical context in which these innovations were applied.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Microexcavation
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g)
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i)
j)
PQ060C
25 µm
25 µm
10 µm
100 µm
k)
l)
m)
n)
CM
PQ020
200 µm
200 µm
50 µm
20 µm
o)
p)
q)
r)
CM
PQ044
50 µm
100 µm
100 µm
s)
t)
u)

◂**Fig. 6** El Pesquero site. Unalloyed copper sheathing sheet PQ060D: **a** Cross sections (CS) viewed under LM, etched; **b** CS under SEM, non-etched. Tacks composed of quaternary bronze exhibit a dendritic microstructure: PQ060A, B, C, and PQ020. PQ060A: **c**, **d** CS under LM, non-etched; **e**, **f** CS under SEM, non-etched, showing non-metallic and metallic inclusions. PQ060B: **g**, **h** CS under LM, etched; **i**, **j** CS under SEM, non-etched, showing Pb segregates. PQ060C: **k**, **l** CS under LM, etched; **m**, **n** CS under SEM, non-etched, showing non-metallic and metallic segregates. PQ020: **o**, **p** CS under LM, etched; **q**, **r** CS under SEM, non-etched, showing non-metallic and metallic segregates. Square nail of quaternary bronze PQ044: **s**, **t**, **u** CS under LM, etched. Etching: hydroalcoholic ferric chloride

The tropical conditions and specific contexts of the studied wreck sites have led to significant corrosion of the fastenings and sheathing; in brasses, dezincification in the marine environment was a major factor. In this work, the microstructure and composition of samples were examined in areas unaffected by corrosion to identify the manufacturing processes and material characteristics. Given the advanced state of degradation of the archeological remains, this research highlights the importance of developing a detailed record and analysis of samples. Such documentation is essential for assessing the wreck sites comprehensively, alongside other findings such as guns, hull elements, cargo, and other material cultural carried on board. This is especially crucial in contexts where wooden hulls have been almost destroyed by the action of wood-boring organisms.

This research demonstrates the value of integrating historical, archeological, and archeometric data to reconstruct the technologies used in modern naval shipbuilding. Such an interdisciplinary approach enriches our understanding of both the materials and techniques used for copper-based artifacts applied to wooden shipbuilding. To advance this research, further historical review is needed to identify three of the four wrecks and establish the nationality of the vessels. Moreover, analyzing other types of archeological remains, such as the wood species used in shipbuilding, could greatly enhance our current understanding of the sites and can also offer a more comprehensive insight into the construction and navigation practices of the period.

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