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ARCHAEOMETALLURGICAL ANALYSIS OF MARITIME STEEL NAILS FROM CRUSADER JAFFA, ca. 13TH CENTURY AD

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ABSTRACT

The harbor town of Jaffa (Tel Yafo) was vital for the medieval Crusader States, functioning as a place where reinforcements, pilgrims, and communications entered the Latin East. An assemblage of five ship nails from Jaffa that were removed for reuse in the 13th century AD are examined and shown to be informative for understanding Crusader iron production, economic sustainability in the Crusader States, and the connections between northern European and Mediterranean ship construction traditions. Archaeometallurgical analyses of these ship nails demonstrate the first metallographically documented examples of Crusader steel recovered from archaeological contexts, as well as rare evidence of uncorroded Crusader alloys (non-numismatic). The analysis also provides likely evidence for the use of iron hardware from the northern European tradition in the Crusader-period Levant.

KEYWORDS: Levant; Crusades; Middle Ages; SEM-EDS; metallography; shipbuilding; ship nails; ferrous metallurgy

1. INTRODUCTION

Salvage excavations were conducted just northeast of the Jaffa Tel at Be'eri in 1965 due to the construction of a bomb shelter for a high school, currently the Amal Technological High School of Tel Aviv (Figs. 1 and 2). A cache of Crusader-period artifacts were excavated on the floor of a mudbrick feature (Fig. 3), including five clenched nails (Fig. 4), and a coin (Fig. 5) minted for John of Brienne, King of Jerusalem from AD 1210 to 1225 (Metcalf, 1995). The humble 13th-century AD Crusader nails are noteworthy for a number of reasons that shed light on local availability of iron, trade and travel patterns, and Crusader-period iron production. The nails are most likely ship nails extracted for reuse locally, potentially suggesting a shortage of iron in 13th-century AD Jaffa, which is also attested in historical documents. The morphology of the nails is characteristic of a tradition with origins in northern Europe, providing archaeological evidence of northern European-type ships in the Mediterranean. Finally the nails are fashioned from iron with substantial steel phases that represent the first documented evidence for steel in Crusader archaeology.

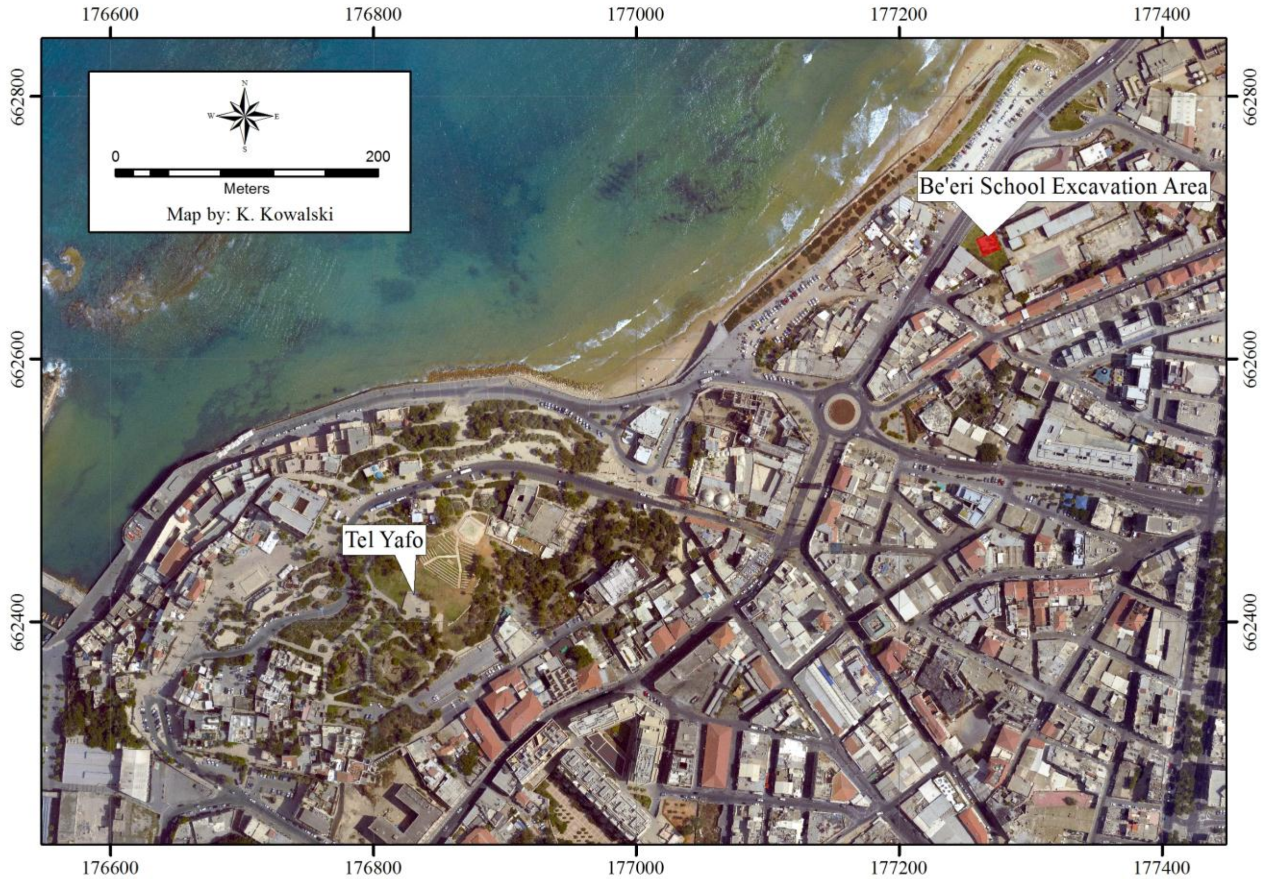

Figure 1. Site of Jaffa and Be'eri excavations.

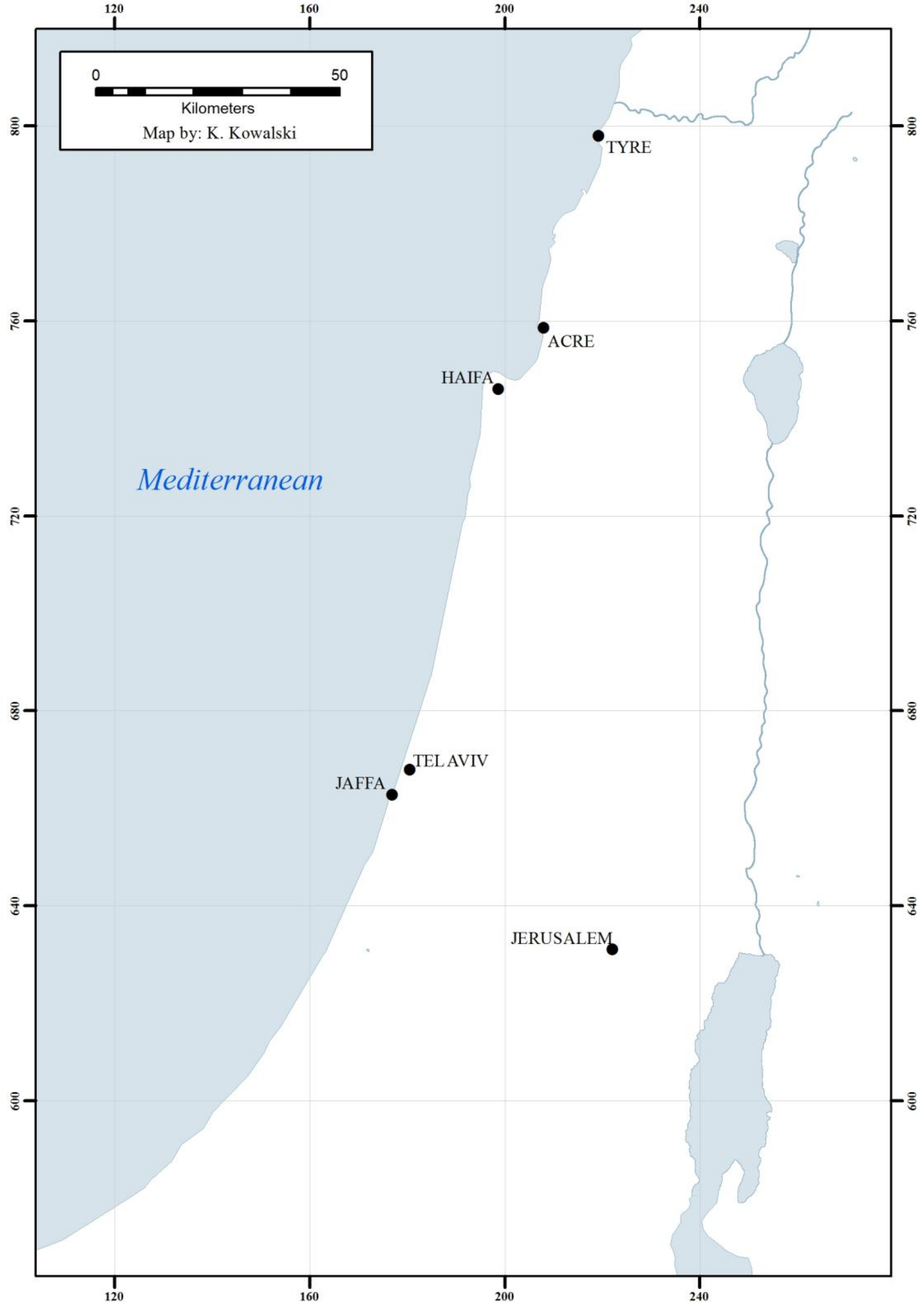

Figure 2. Be'eri, Jaffa, and other major Crusader sites in Levantine regional context.

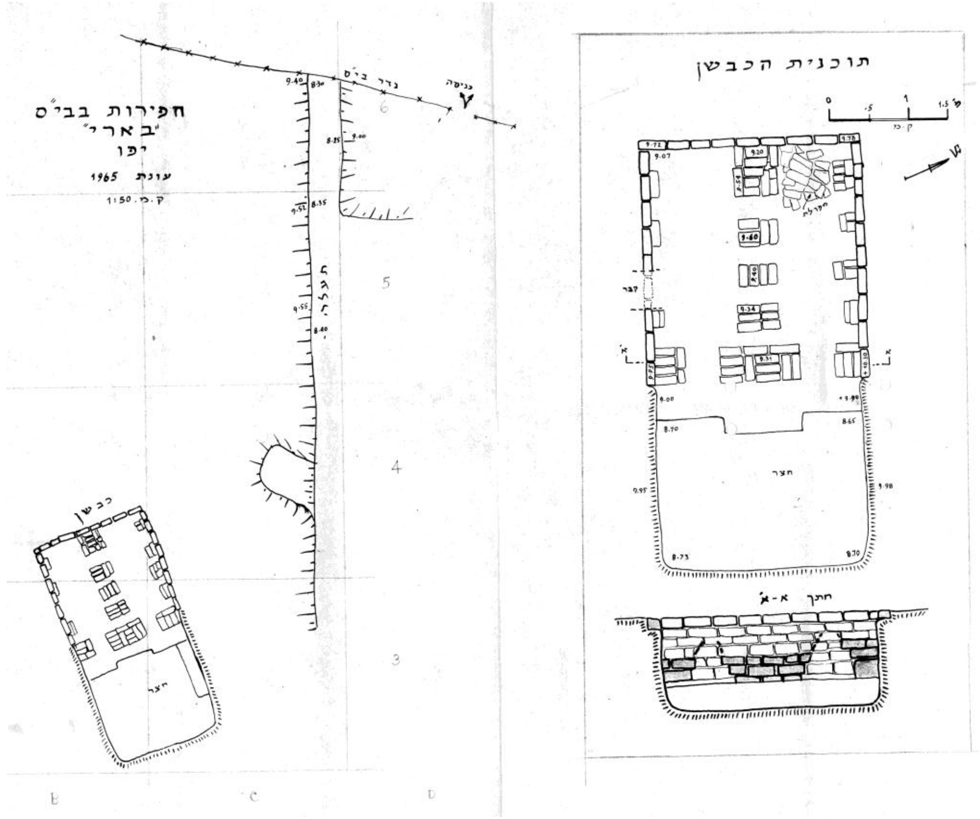

Figure 3. Plan of the complex wherein the Crusader nails and coin were found from Kaplan's 1965 salvage excavations.

1.1 *Crusader Jaffa*

Jaffa, a small natural harbor on the Mediterranean coast, played an important role during the Crusades as it offered the closest port access to Jerusalem. The roughly 170-year history of Jaffa as a Crusader port begins with the conquest of the town by the First Crusaders in 1099, after which it periodically fell to Muslim forces for shorter periods before finally being conquered by the Egyptian Mamluks in 1268 (Boas, 2011). Early in the Crusades, Jaffa became the first Crusader harbor and a major center for import and export of goods as well as for ferrying European pilgrims, merchants, and Crusaders to the Holy Land. Since its first days as a Crusader port, ships were scuttled in order to provide scarce materials for the invading forces. Genoese ship parts from Jaffa were used to construct three siege towers for the First Crusade attack on Jerusalem. These recycled items included timber, tools, and nails (see Boas, 2011 and citations therein, specifically Raymond d'Aguilers, 1969; William of Tyre (Willelmus Tyrensis), 1986).

Although its location brought it to prominence, Jaffa's port was relatively inhospitable and dangerous due to its small size and rockiness, and later was overtaken in standing by the ports of Acre (Tel Akko) and Tyre. Throughout its history Jaffa nevertheless remained a strategic staging point for Crusader armies. In 1102, after a crushing defeat in the plains of Ramla, the Crusaders managed to hold out behind the walls of Jaffa until Baldwin I arrived on a commandeered English pirate ship (Asbridge, 2010, 132). The English ship mentioned in this text indicates that northern European ships were present in local waters by this time. Ship nails that appear to match the northern European tradition are therefore not an unexpected find in the Crusader contexts in Jaffa (see Discussion).

In the early 13th century AD, during the period from which the nails and coin in Jaffa derive, the harbor changed hands several times. In this period, the fluid and pragmatic aspect of trading and commodities exchange is indicated historically by a trade agreement between the Mamluk Sultan Baybars and John of Ibelin, the Count of Jaffa, which gained peace for Jaffa in exchange for the right of the Mamluks to import grain to Muslim Syria through the port of Jaffa. This reminds us of the international and mixed maritime influences in these Crusader period harbors, and cautions against any tendency to uncritically associate maritime-related archaeology from this period with European vessels alone. Be that as it may, comparative typological work of contemporary nails has been a major topic of research, fortunately providing a wealth of comparanda for the Be'eri nails.

1.2 Excavations of Crusader Jaffa

The occupation evidence and chronology provided by the archaeological investigations in Jaffa are consistent with descriptions in the historical sources, and deepen our understanding of life in Crusader-period Jaffa. The bulk of the Crusader archaeological remains from Jaffa come from the Ganor compound, excavated from 1999-2007. By the modern Clock Tower, excavations revealed the erection and maintenance of streets (Peilstöcker, 2009). Salvage excavations at the modern Flea Market yielded remains of a massive fortification wall, as well as indications of a Crusader storage facility, and what may be evidence of ovens. Ceramic remains from the Crusader period at Jaffa indicate a substantial Frankish presence in the harbor city, with pottery dates ranging from the 11th-mid 13th centuries AD (Burke, 2011; Peilstöcker and Burke, 2011). The Crusader stratum from the Flea Market excavations is superseded by a burnt destruction layer after which the site was abandoned except for use as a Mamluk burial ground (Peilstöcker et al., 2006).

Salvage excavations just northeast of the Tel in 1965, within about 200 meters of the modern coastline, revealed evidence of a complex that the principal investigator, Jacob Kaplan, interpreted as a bakery or kiln (Fig. 3; Kaplan, 1966). Kaplan wrote memoranda and took field notes, but the excavations at Be'eri remained unpublished until the recent renewed interest in the city's history and archaeology undertaken by the Jaffa Cultural Heritage Project (JCHP; Burke et al., 2017a) .

The five nails and Crusader coin were excavated together as a deposit in Locus-1 (L-1). The finds may have been associated with what Kaplan identified as an ashen layer (Burke et al., 2017b, Appendix). However, the nails and coin themselves showed no evidence of burning or alteration by fire, most likely precluding post-forging microstructural alteration. Furthermore, the medieval-era Crusader cache of finds were found in what has been determined to be an Early Roman tomb, misidentified by Kaplan as a medieval kiln complex, indicating that the nail and coins are purely intrusive. No finds postdate the early 13th century AD in the excavation unit. Medieval ceramics were recovered in other excavation squares not in direct association with the nails and coin. The area later served as an Ottoman period cemetery (for Ottoman metallurgical practices, see Nerantzis, 2009).

The coin is therefore considered the *terminus post quem* for the small deposit (see Burke et al., 2017b for full discussion of context, as well as Zori and Kaufman, 2017). The original excavation report dated the coin to the reign of Baldwin IV (AD 1174-1185). A later revision by the Jaffa Museum identified the coin using Metcalf's (1983, 1995) comprehensive Crusader coin study as one minted by John of Brienne (AD 1210-1225), perhaps in Acre sometime after 1219 (Metcalf, 1995, 81). The authors agree with the latter identification. The vast majority of John of Brienne deniers, including the Jaffa exemplar, are known to be struck with various similar inscriptions; obverse +IONES REX, iconography of cross pattée, annulets in second and third quarters; reverse inscriptions show +DAMIATA, with iconography of crowned bust and lockets. In rare cases the legends are reversed, with obverse +IOHANNES REX showing a facing head, and reverse +DAMIETA with cross (Metcalf, 1983, Plate 7, no. 122; also cf. the updated Metcalf, 1995, Plate 12, 203-205). The obverse of the Jaffa coin clearly has +ION[ES] [RE]X, and the reverse seems to display D[AMI]A[T]A. The iconography on the obverse, with cross pattée and annulets in the second and third quarters, supports identification of this coin as a common one of John of Brienne (Fig. 5).

Figure 4. Crusader clenched nails from Jaffa. Clockwise from upper left: 79-3488-65-003 (MHA 2378), 79-3488-65-004 (MHA 2379), 79-3488-65-005 (MHA 2380), 79-3488-65-006 (MHA 2381), 79-3488-65-007 (MHA 2382).

Figure 5. Jaffa coin of John of Brienne (IAA 47582=MHA 452), obverse (Credit: Old Jaffa Museum of Antiquities).

1.3 Crusader and medieval archaeometallurgy

Steel is an alloy of iron and carbon with the latter's composition most often being around 0.30 – 1.00 wt% C, but under 2.1 wt% C (Davis, 1996, 15). Although medieval European smiths still widely employed direct or bloomery ferrous metallurgy, the indirect method of iron or steel production was also developed in Europe in the 12th century AD (Buchwald and Wivel, 1998; Dillmann and L'Héritier, 2007). Steel is rare and not well-documented for the early to central Middle Ages (Pleiner, 1969, 484). But it should not be surprising to find evidence for steel production in this period at Jaffa when ferrous materials were still produced mostly by the bloomery process, especially given the antiquity of intentional steelmaking in the Roman world (Tylecote, 1987; Starley, 1999; Lang, 2017).

Crusader archaeometallurgy of ferrous metal or copper alloy artifacts is characterized by a paucity of metallographic and compositional analysis of artifacts from sound archaeological contexts (but see Ponting, 1999 for a useful attempt toward rectifying this situation). Some archaeometallurgical literature on coinage has been published (Al-Kofahi and Al-Tarawneh, 2000; Giumlia-Mair, 2005). The comprehensive publication of iron Crusader remains by Ashkenazi et al. (2013) may be the first archaeometallurgical analysis of ferrous artifacts of the Crusader period to date. They selected six arrowheads (from a rich corpus of over 1200), and three iron bolts from the Crusader castle of Arsuf for analysis. These remains came from a mixed Crusader/Mamluk destruction layer, and the authors believe that most of the weaponry should be attributed to Mamluk use. Whatever the case, no evidence for steel was found, only wrought iron (Ashkenazi et al., 2013, 253-4).

There is no known evidence for Crusader smelting, smithing, recycling, or mining activities, but these surely occurred. It remains a problem for archaeometallurgists to determine conclusively accidental experimentation versus intentional alloying in any context. The lack of robust data on other Crusader alloys also limits our ability to make comparisons. However, in the Be'eri case, the ample evidence for spheroidization of cementite phases is clear evidence for intentionality of production and shows that steelmaking was a deliberate choice (see Results). Furthermore, there is a good deal more known about the metallurgical practices of contemporary medieval Europe, against which the Be'eri nails can be compared.

Scarce historical documents on the metallurgical process of the European Middle Ages have left archaeology as the major source for information regarding this period's metallurgy, and the few historical records relating to metallurgy were usually written by accountants or historians, not by smiths (Tylecote, 1962, 269). From the historical sources, it is clear that smithing was carried out in various degrees of specialization and organization. In her study of medieval Scandinavian blacksmiths, for example, Thålin-Bergman (1979, 102) identifies five types of blacksmith: 1) household smith who repaired simple objects, 2) smith who practiced smithing as a supplement to a primarily agricultural occupation, 3) smith who practiced fairly specialized manufacture by taking advantage of locally available and high quality raw materials, 4) the itinerant and specialized smith who practiced smithing full-time, 5) the apprentice or assistant smith. From the historical sources it is also apparent that monastic orders across 12th-13th-century AD Europe often sponsored and executed ironworks on their properties (Pleiner, 2000, 276-7). Monastic orders in England were also granted iron and coal mining rights in the 12th-14th centuries AD. The Domesday Book of AD 1086 recounts that bloomeries were ubiquitous in the southwest of England such as at Somerset, with iron smelting common elsewhere at locations in river valleys such as Staunton and Aldford where hydraulic systems were likely being used to power the furnaces (Tylecote, 1962, 269-73).

Crusaders relied to a large extent on imported or prefabricated metals, brought from Europe or perhaps traded with Near Eastern local polities, including the various Islamic communities. During the Fourth Crusade (AD 1202-1204), the Venetians provided ironwork to the Templars (Boas, 2011, xx; Pleiner, 2000, 280). There are archaeological indications that local copper mines were exploited by the Islamic polities in the Levant, with a slag heap at Faynan (Hauptmann, 2007, fig. 5.4b; Grattan et al., 2013), and other limited evidence of copper and lead smelting (Hunt et al., 2007).

Smiths understood that combining softer iron with harder steel could improve the properties of iron objects (Carpenter and Robertson, 1930a, b). In the Middle Ages, edged objects such as knives and swords were often made with a sharp and hard steel edge buttressed by more malleable wrought iron (Tylecote, 1987, 263; McDonnell, 1989; Ottaway, 1992). British steel metallurgy by the time of the Crusades demonstrated all of the layering, welding, and piling techniques described by Tylecote and Gilmour's Types 1-3 (1986, 2-3, table A3). Various iron and steel blades and tools, mostly knives, dating from the 12th-14th centuries AD at Winchester, Chingley/Kent, and Goltho/Lincolnshire, some dated firmly to the 13th century AD, show evidence for production techniques such as homogeneous carbon steels, welding of iron to steel, alternate layering of ferrite and ferrite+pearlite phases, hardened martensite phases, and arsenic enrichment (Tylecote and Gilmour, 1986, 44-51, 84, 113). As all of this previous research illustrates, the information presented in the current study provides underrepresented Crusader metallurgical data that concur with the otherwise well-researched field of contemporary medieval European metallurgy (cf. Hoffeld, 1969; Tholander, 1975; Brewer, 1976, 1981; Coghlan and Tylecote, 1978; Hayes, 1978; Bjorkenstam, 1985; Rose et al., 1990; Buchwald, 2005; Wärmländer et al., 2010; Dandridge and Wypyski, 2011). Given the scarce nature of well-contextualized iron or steel implements from the Crusader era, metallographic and compositional analyses were carried out on the Jaffa nails in order to add metallurgical dimensions to what we know historically and archaeologically regarding contemporary trends in production and consumption.

2. MATERIALS AND METHODS

Samples from four of the five nails were selected for metallographic and compositional analysis. Artifact 79-3488-65-006 was not mounted and has been preserved for conservation purposes and future analysis. Samples were cut with a saw, prepared as cross-sections using a two-part epoxy resin, ground, and polished. Light optical microscopy (LOM) was conducted with a Nikon Epiphot-TME metallographic microscope, while micrographs were captured with either a Nikon digital camera D3000 or a 14 MP eyepiece digital camera UCMOS series microscope camera, with ToupView 3.2 image software. When noted in captions some images were taken using differential interference contrast objections (DIC) and red compensator plate with polarized light on the Epiphot-TME. Micrographs were taken first on an unetched, polished surface, followed by etching with 2% nital.

Variable pressure scanning electron microscopy with electron x-ray energy dispersive spectroscopy (VPSEM-EDS) was used for analysis of the four nails. The instrument belongs to the Molecular and Nano Archaeology Laboratory (MNA) of the Cotsen Institute of Archaeology, and is a FEI NovaNano field emission gun (FEG) variable pressure (VP) SEM-EDS. All of the micrographs presented in the figures were captured either with metallographic light optical microscopy, or with the VPSEM gaseous analytical detector (GAD) detector in low vacuum.

Iron ore and slag standards were analyzed using accelerating voltage of 15 kV, on low vacuum with pressure of 50 CPa, with adjustments made in intensity and aperture for imaging in order to estimate margins of error (see Kaufman, 2014 for analysis of standards). For the experimental results of the nails themselves, accelerating voltage of 18 kV was used.

Qualitative, relative carbon contents of the samples were averaged over five random spots at x1500 magnification, excluding areas with slag in order to gauge carbon content of the alloys themselves. Like high carbon contents, presence of slag in iron alloys causes an increase in hardness and embrittlement, which decreases the workability of the nails. EDS does not yield reliable absolute measurements of carbon content, further compounded by possible carbon contamination from the epoxy resin polishing suspensions, but the relative amounts of carbon wt% are indicative of variations between the phases. When carbon is reported below, it is to be considered qualitative or representing presence of carbon.

3. RESULTS

Archaeometric analysis was conducted on two nail heads and two nails shanks. Three nails can reasonably be called steel (79-3488-65-003, 79-3488-65-005, 79-3488-65-007), and one should be considered a steeled wrought iron (79-3488-65-004). Ferrite and cementite in the form of spheroidal pearlite predominates this corpus, with consistent evidence of lamellar pearlite as well. Spheroidization occurs as the steel is held or cooled slowly below the A_1 temperature at which austenite forms, 727°C. Excess spheroidal phases of cementite, or partially spheroidized pearlite do not necessarily confer optimal mechanical properties. Partially spheroidal pearlitic structures arise from heating in 450-500° C range, without conferring many beneficial effects. The carbide lamella in the pearlite become partially spherodized during what can be considered detrimental annealing episodes. However, importantly, cementite spheroidizes only following heat treatments lasting several hours, and in successful cases can serve to harden the iron and improve ductility by breaking up the pearlite lamellae (Samuels, 1999, 165; Scott, 2013, 271-2). Therefore, spheroidization is an intentional process, clear evidence for intentionality of steel production.

No traces were recorded of post-depositional burning in the L-1 cache which may have altered the microstructure of the finds (Fig. 4). Some select additional micrographs of these artifacts are published in Zori and Kaufman (2017), but the full final report of the nails is found below.

3.1 Steel nail shank 79-3488-65-003

The characteristics of this nail shank are ubiquitous pearlite phases found among equiaxed ferrite grains, some spheroidal pearlite and carbides, nitride or carbonitride needles, and fayalitic slag that possesses strontium and barium impurities remnant from the smelt (Figs. 6-8), although barium can also be present in the slag of objects that were reduced in the direct process (Buchwald and Wivel, 1998, 92). Evidence of wüstite in the fayalitic slag inclusions is scarce.

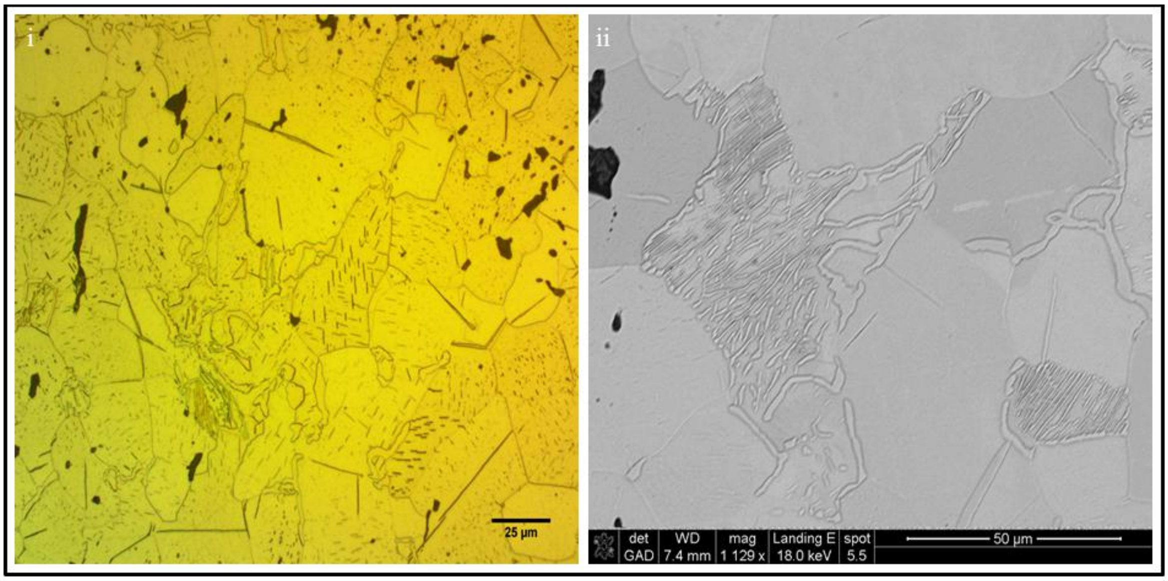

Figure 6. i) Ferrite, lamellar pearlite, spheroidal pearlite and carbide, nitride needles, fayalitic slag, x40 magnification, LOM; ii) close-up of lamellar pearlite, x1,129 magnification, SEM. 79-3488-65-003.

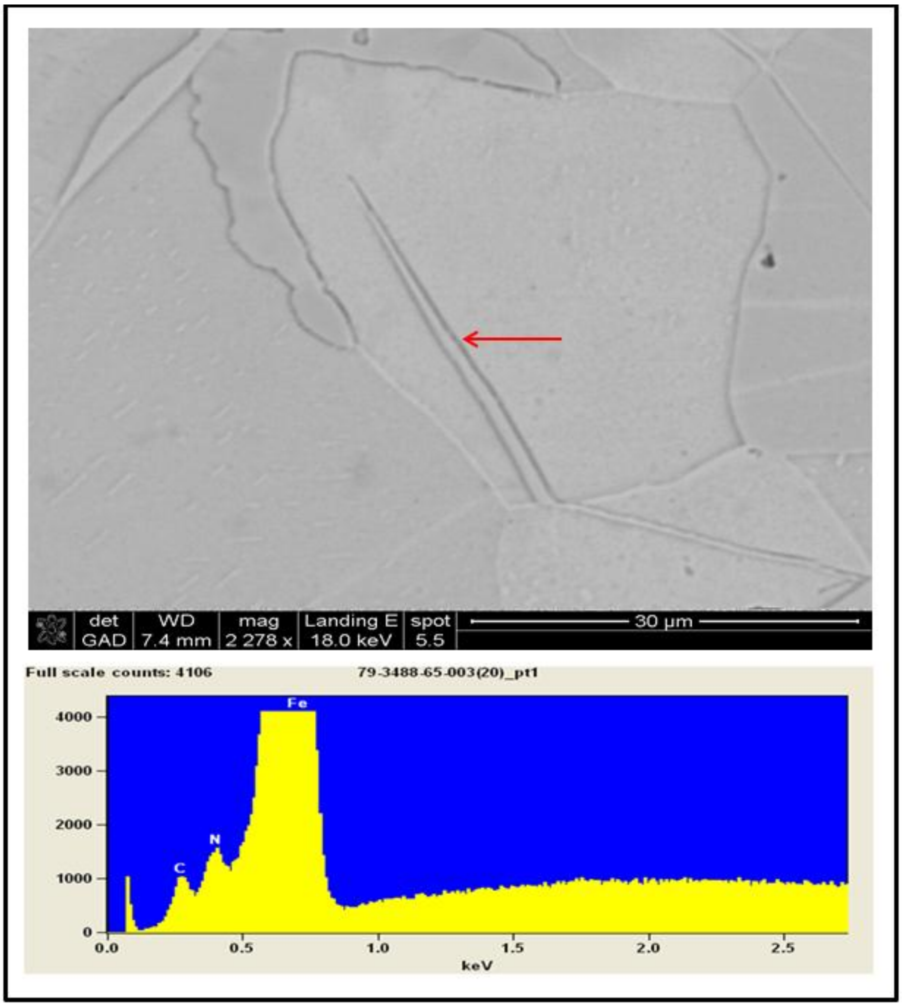

Figure 7. SEM micrograph and representative EDS spectrum of nitride or carbonitride needles (indicated by red arrow) found throughout the sample, x2,278 magnification. 79-3488-65-003.

Carbide or cementite appears in both spheroidal and lamellar forms. The abundance of pearlite demonstrates intentional steeling, but the partially spheroidized phases and carbides, along with the high quantity of slag impurities, show a degree of laxity in the forging environment.

Spot analysis on the nitride needles indicates that their composition is carbon rich (Fig. 7), with composition of 93.17 C, 4.85 N, and 1.98 C (qualitative) leaving open the possibility that they may be carbonitrides. The nitride needles appear consistently throughout the sample. Nitrides serve to harden steel, and combined with the pearlite and ferrite formations, would make this nail both hard and malleable.

Table 1 shows the average overall composition of the nails. These results are not to be taken as the real carbon content, but rather reflects the fact that EDS is not an ideal method to quantify absolute figures for carbon content in iron alloys, and also highlights potential carbon contamination from the epoxy resin. This table is included as a comparative basis to examine the intra-assemblage carbon content, not as a real wt %. It is a qualitative report for carbon content – based upon microstructure it is clear that these are not high carbon steels.

The slag is overwhelmingly characterized by fayalitic or glassy phases, with limited amounts of iron oxide phases (likely wüstite) on the slag interface with the metal, pure iron globules or prills, and ore remnants of strontium, barium, and sulfur (Fig. 8). The fayalitic phases of the slag impurities contain Na, Mg, Al, Si, Ca, Ti, Mn, K, C, P, and of course Fe and O in varying degrees.

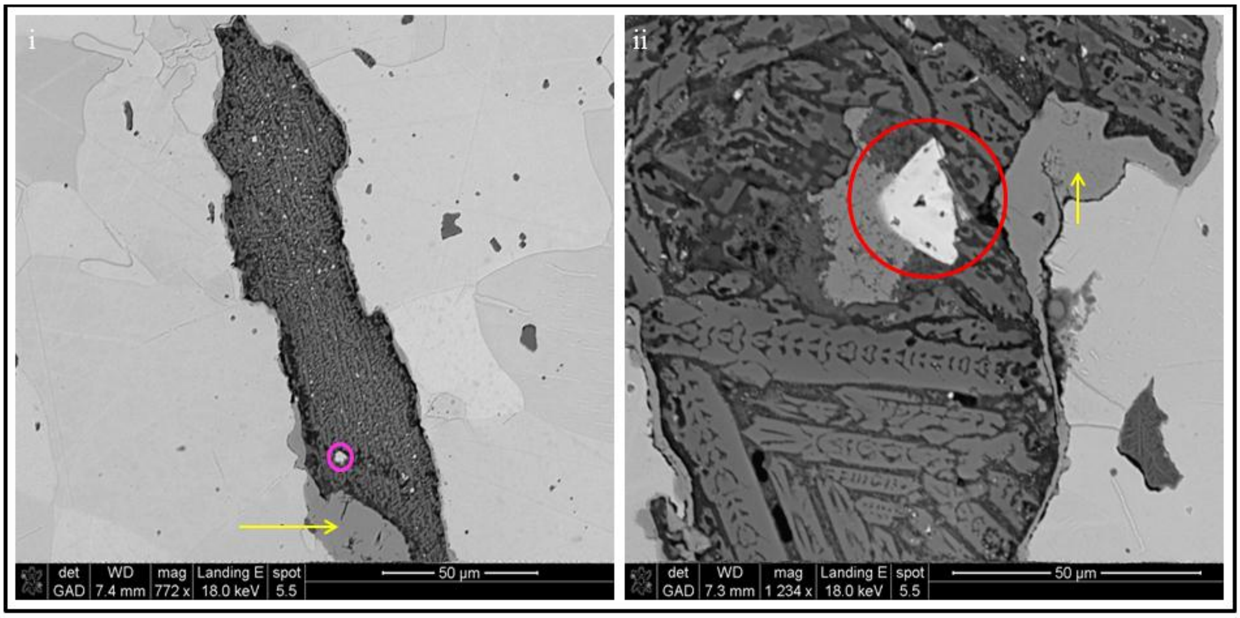

Figure 8. i) Fayalite-rich slag, pure iron globule/prill in pink circle, yellow arrow pointing to likely wüstite zone, x772 magnification, SEM; ii) strontium (9.26 wt%), barium (40.81 wt%), and sulfur (14.07 wt%) ore remnant in red circle, with yellow arrow pointing to the wüstite border of the mostly fayalitic slag, x1,234 magnification, SEM. 79-3488-65-003.

Table 1. Relative, qualitative composition of iron alloys in wt%, EDS (not quantitative or absolute).

Artifact information	Fe	C	Si	P
79-3488-65-003 (shank)				
Composition wt%	97.5	2.5	–	–
RSD %	0.26	11.66	NA	NA
79-3488-65-004 (head)				
Composition wt%	98.9	1.0	0.1	–
RSD %	0.41	46.53	59.07	NA
79-3488-65-005 (head)				
Composition wt%	98.1	1.7	0.1	0.1
RSD %	0.32	22.30	21.18	100
79-3488-65-007 (shank)				
Composition wt%	98.6	1.4	–	–
RSD %	0.37	24.38	NA	NA

3.2 Steel nail shank 79-3488-65-004

This nail head is by and large wrought iron with some clustered pearlite phases. Employment of DIC and red compensator plate demonstrate the largely uniform grain size (Fig. 9i-ii). However, some zones with differential grains may indicate welding episodes (Fig. 9iii). Figure 10 shows good evidence of a weld, with the other characteristic aspects of this sample. In the upper portion, slag stringers abound in two distinct zones, the top with uniformly medium-sized grains. Directly below this the stringers are interspersed between fine equiaxed ferrite grains. In the bottom portion, pearlite oases are clustered among grain sizes of vastly differing proportions, some relatively massive. The smelting and forging was conducted with skill, as the wrought iron is mostly devoid of carbon content. Carbon content is mostly in the form of pearlite, and rarely spheroidal (Fig. 10).

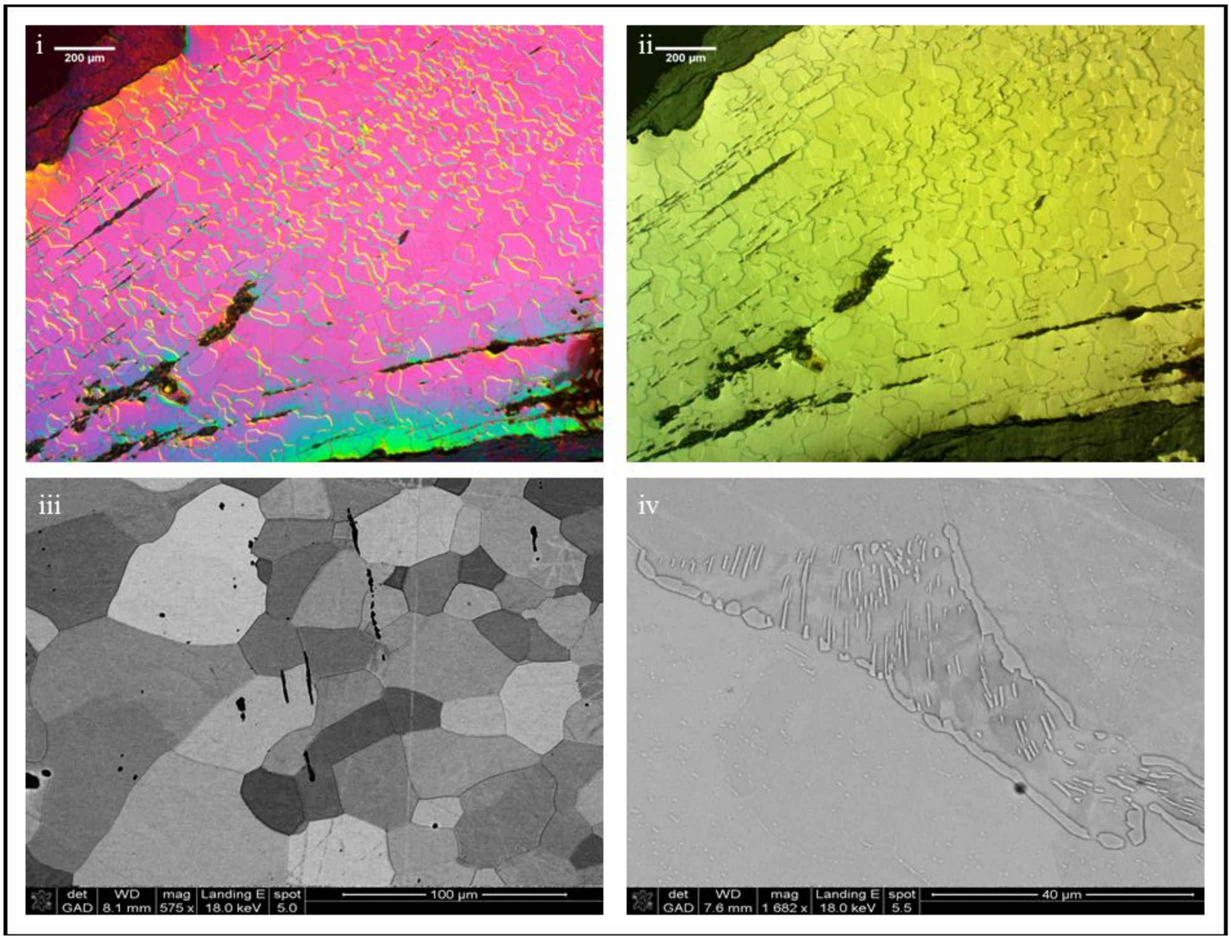

Figure 9. i) DIC and red plate compensator showing equiaxed ferrite matrix and wüstite-rich slag inclusions, the curve in the lower right is where the nail head meets the shank, x5 magnification; ii) DIC (without red plate compensator) of i, directionality of slag stringers and ferrite grains indicate working, x5 magnification; iii) differentially sized ferrite grains, x575 magnification, SEM; iv) pearlite, x1,682 magnification, SEM. 79-3488-65-004.

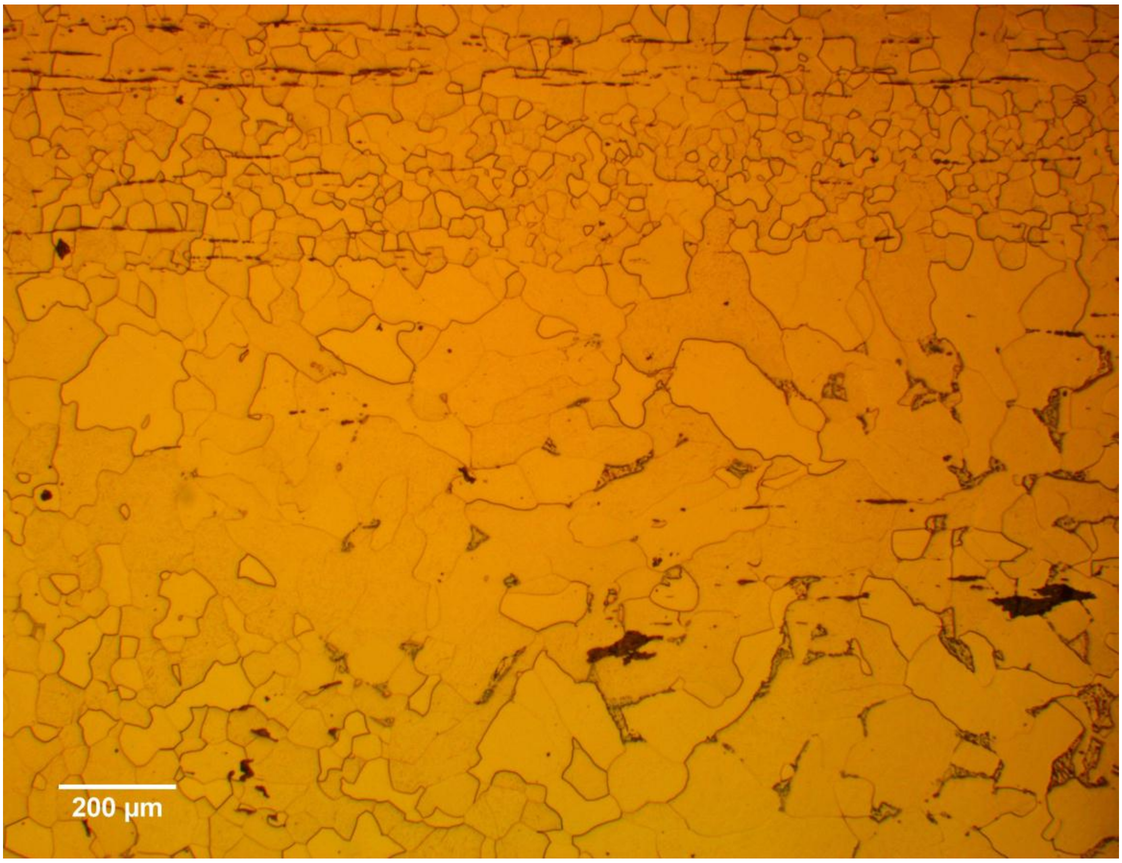

Figure 10. i) weld, with small, equiaxed ferrite grains and slag stringers on top, and large ferrite grains on the bottom with clusters of pearlite on the lower right, x5 magnification, LOM. 79-3488-65-004.

Figure 11 shows a pearlitic and carbide zone bordering a wüstite-rich slag. However, the cementite phases in Figure 11 are partially spherodized, in contrast to Figure 10 which shows lamellar pearlite, albeit it in limited, clustered zones. The latter is why the determination of steeled iron, as opposed to steel, is applied to this artifact alone in the corpus. In addition to wüstite, the glassy phases of the slag contain Mg, Al, Si, Ca, Mn, Ti, K, C, P, and minimal S, O, and Fe. The glassy phases also consistently contained Ba, but not as a microstructurally identifiable impurity such as in 79-3488-65-003 (Fig. 8). The directionality of the slag stringers, as well as the grain patterns, indicate heavy working which is consistent with the evidence for welding.

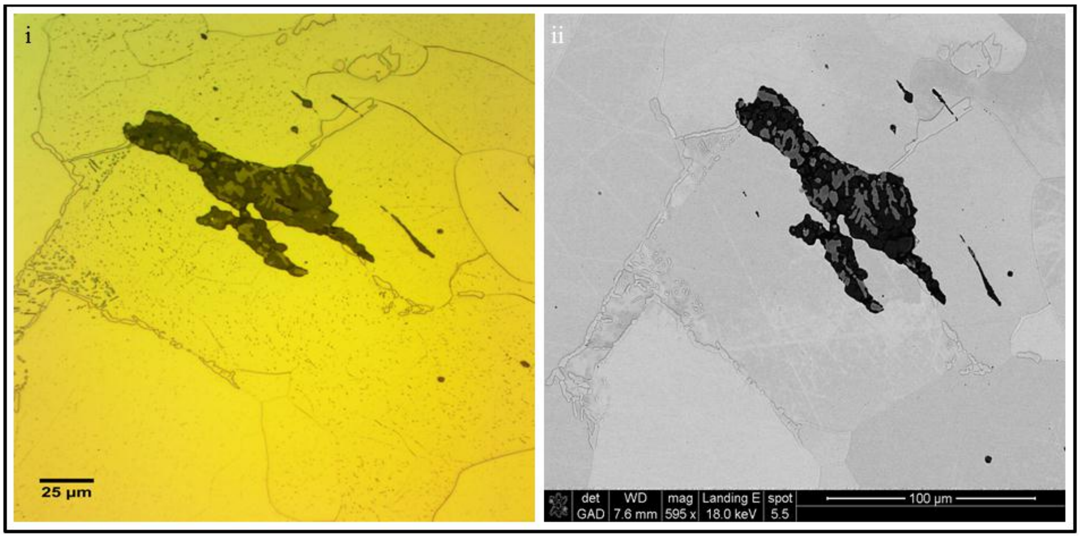

Figure 11. i) (x40 magnification, LOM) and ii) (x595 magnification, SEM) show wüstite-rich slag inclusion in ferrite matrix with lamellar pearlite and carbides. 79-3488-65-004.

3.3 Steel nail shank 79-3488-65-005

There are at least two types of iron alloys within this specimen, perhaps three. There are large ferrite grains with some pearlite or carbides representing low carbon steel, small ferrite grains with spheroidal pearlite, and some large ferrite grains without pearlite or carbides (Fig. 12). The pearlitic phases concentrate along the grain boundaries (Fig. 12i). The sharp boundary zone between some areas of small and large grains means that there was most likely a weld (Figs. 12ii and 13). The directionality of the grain matrix and slag stringers indicates heavy working and repeated annealing. The preponderance of carbides throughout the microstructure shows that this is intentionally produced steel, if not perfectly controlled to yield a higher concentration of lamellar pearlite. The low level of phosphorus may be responsible for the large grain size (cf. Scott, 2013, 100). The glassy slag contains Na, Mg, Al, Si, P, K, Ca, Ti, Mn, C, O, and Fe.

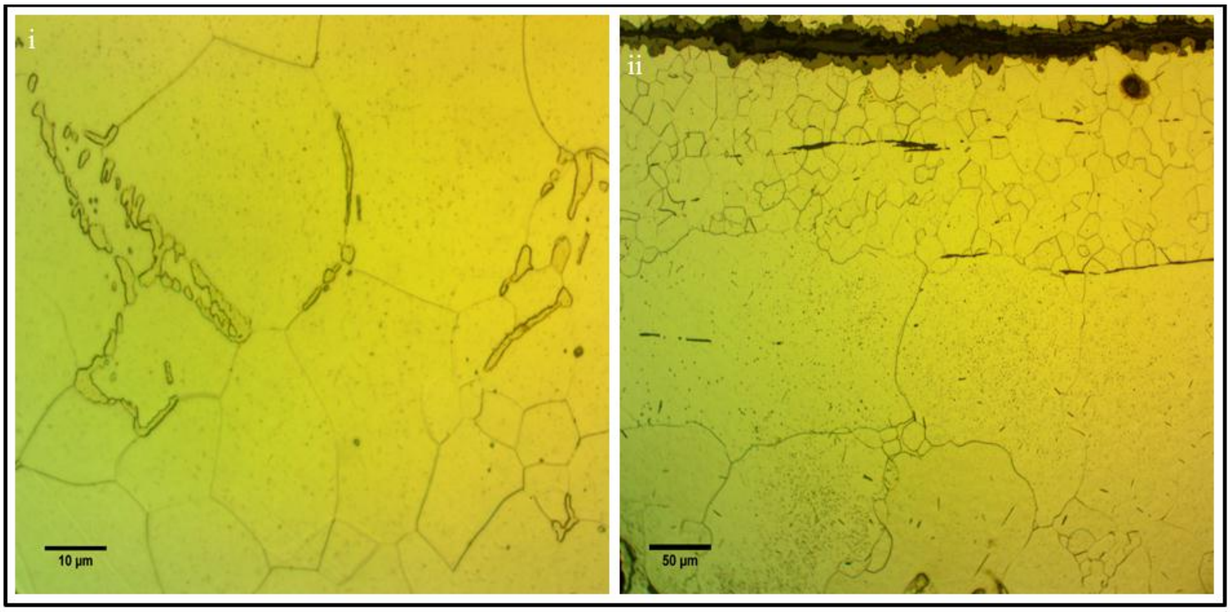

Figure 12. i) large ferrite grains with carbides precipitating along grain boundaries, x100 magnification, LOM; ii) weld and slag stringer on top with large ferrite grains on bottom, devoid of carbon-rich phases, x20 magnification, LOM. 79-3488-65-005.

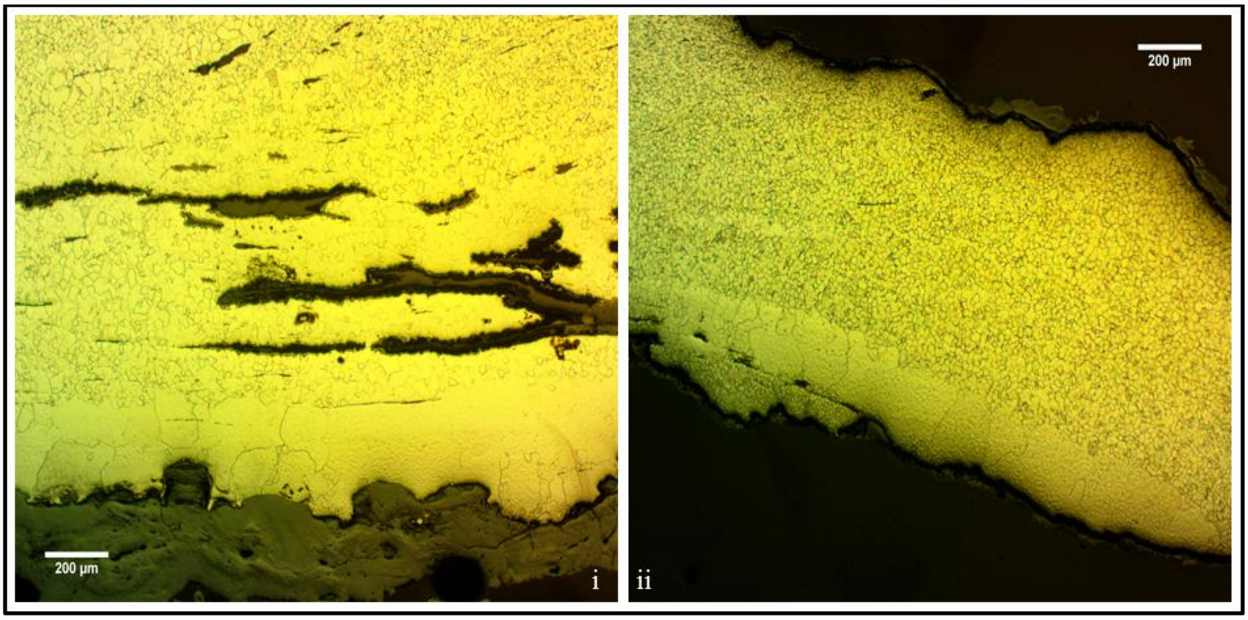

Figure 13. i) The top of the nail head is shown on the bottom of the micrograph with corrosion, then weld and slag stringers above, x5 magnification, LOM; ii) macro-view of the nail head showing the weld zone in the lower portion, x5 magnification, LOM. 79-3488-65-005.

3.4 *Steel nail shank 79-3488-65-007*

This nail shank is a good quality steel that has been annealed, with pearlite in mostly spheroidal and limited lamellar forms (Fig. 14; Scott, 2013, 270-271). There is an abundance of these carbide phases in an alloy matrix that is relatively devoid of slag inclusions (slag containing Na, Mg, Al, Si, P, K, Ca, Ti, Mn, C, O, and Fe, some Ba, all glassy inclusions with quite limited wüstite zones) when compared to the other nails. The grains are mostly differential in size, perhaps due to a variance in carbon content or working. The smaller-sized grains may represent an episode of recrystallization. The spheroidization process for this nail was carried out consistently, although the accumulation of cementite phases along the grain boundaries could have caused some embrittlement.

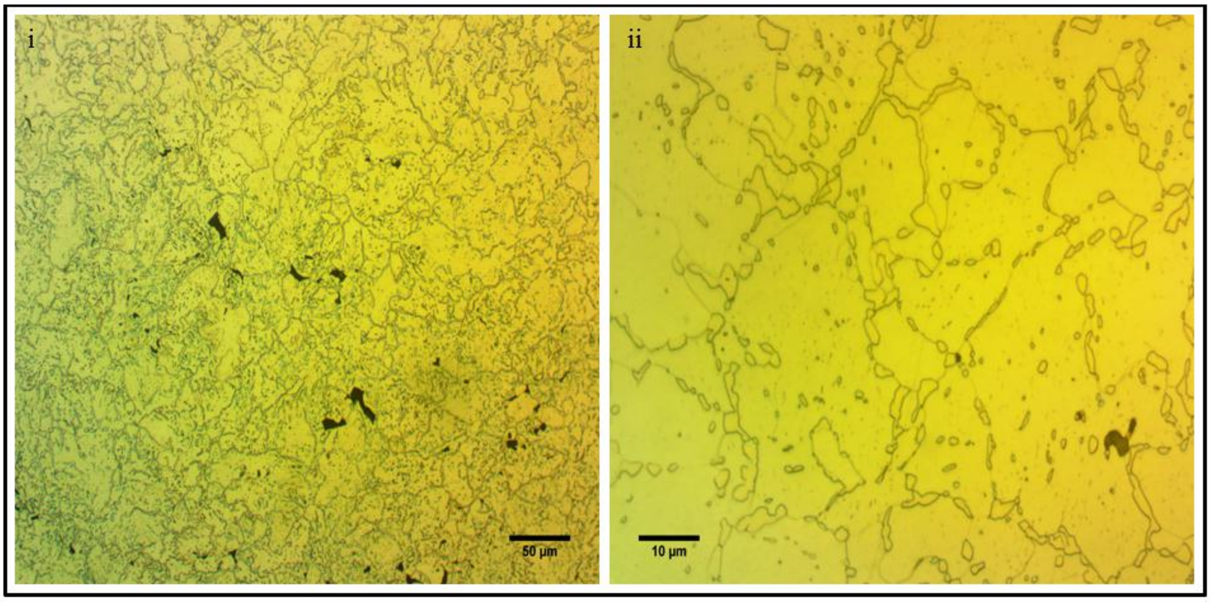

Figure 14. i) (x20 magnification, LOM) and ii) (x100 magnification, LOM) show abundance of carbide phases in spheroidal and lamellar pearlite at various magnifications. 79-3488-65-007.

4. DISCUSSION

4.1 *Ferrous archaeometallurgy*

Archaeologists must always be wary against drawing broad conclusions from a limited dataset such as found at Be'eri. Although the nails from Be'eri represent a small sample, it is useful to discuss their historical and archaeological contexts in order both to frame these limited data properly, as well as to propose potential interpretations and the situation of ferrous metallurgy within the contemporary society. With no other known Crusader alloys preserved in metal form, it is worthwhile to attempt to extract as much information as possible from this assemblage with the hopes that future excavations will yield other well-dated, well-preserved metallurgical finds. Furthermore, the spheroidized cementite phases are clear evidence for intentional steelmaking, ruling out accidental production of these steel alloys that also happen to be highly appropriate for the maritime requirements of ship nails (ductility and hardness) that had to withstand the mechanical stresses of joining wood subjected to sea waves. Due to the extensive heterogeneity of phases and inclusion of impurities, all nails appear to have been produced via the direct process.

The three nails that can reasonably be called steel, or at least have predominantly steel phases, are characterized by glassy slag stringers, whereas the one nail that is largely a wrought iron with minimal steeling is marked by wüstite-rich slags (79-3488-65-004). The presence of wüstite slag in the latter accords well with Buchwald and Wivel's (1998) predictive correlations between wüstite slag and wrought iron.

Buchwald and Wivel (1998, 94) state that glassy or fayalitic slags predominate within pearlite-rich matrixes, as opposed to wrought iron ferrite-rich ones. Their assessment is well borne-out by the archaeometallurgical results presented here. This is generally the case when taking each alloy into account. However, some localized areas do not always abide by the rule, as seen in Figure 11 with a wüstite-rich slag adjacent to some lamellar pearlite and carbides.

The lack of austenite or martensite phases in this nail corpus is consistent with the function of the nails, lacking cutting edges but needing the strength and malleability for maritime activities that could be achieved by the various cementite and ferrite phases. It has been shown in earlier periods that bigger nails tend to have higher carbon content than smaller ones, indicating that smiths were able to be selective in their production techniques regarding carbon content (Angus et al., 1962).

Barium is attested in nails 79-3488-65-003, 79-3488-65-004, and in trace amounts in nail 79-3488-65-007. This may be further evidence that the direct process was being employed in the production of these nails, but further research into the slags along the lines of Dillman and L'Héritier (2007) will have to be conducted to confirm this. Strontium is only attested in nail 79-3488-65-003. It may be that the combined Sr, Ba, and S contents only occur in one nail because of differences in the working process, but it may be more likely that different ore sources are attested here within one corpus. Given the international nature of the Crusades, this is hardly surprising.

4.2 *Nail typology and shipbuilding traditions*

The nails recovered at Jaffa/Be'eri appear to be from ships or boats, probably used originally to fasten together overlapping planking in the hull. The nails show evidence of having been clenched into a 90-degree angle along the face of the planking to prevent them from drawing out. The nails were subsequently extended back to roughly 45 degrees for removal from the ship-planking (Fig. 4). McGrail (2004, 150-2, fig. 1.4) calls this type of nail 'turned nails' which are clenched directly on the wood without a washer or rove and not hooked back into the wood. McGrail argues that this type of nail is characteristic of the shipbuilding tradition in southern England. If this typology is correct, it might indicate that these nails derive from a ship constructed in northern Europe, or forged locally by smiths trained in this tradition.

The medieval ship traditions in northern and Mediterranean Europe differed substantially in developmental trajectory and construction methods. The northern European tradition around the North Sea was dominated by a shell-first construction and planks fastened together with iron clench nails, clench bolts or boat rivets, and varying usage of wooden pegs (Bill, 1994; Crumlin-Pedersen, 1994; McGrail, 2004; Zori, 2007). In the Mediterranean, the ships were constructed frame-first with wooden mortise-and-tenon construction or frame-first with planking nailed to the frame (Kahanov, 2003, 49; Pedersen, 2008, 90). During the Crusades this regional separation substantially decreased, especially after the Third Crusade when large numbers of ships from northern Europe entered the Mediterranean for the first time since the Roman period. The intermixing of ship traditions began especially after the Iberian Reconquista opened the Strait of Gibraltar to unrestrained Christian shipping in the mid-13th century. Evidence of the technology transfer between the Mediterranean and the Atlantic shipbuilders includes for example the introduction of carvel construction, stern rudders, and fore/aft towers to northern European ships, and the appearance of single-mast cogs in the Genoese fleets of the Mediterranean (Kreutz 1976; Bill and Roesdahl 2007; Cunliffe 2017). In the context of the beginnings of the intermixing of ship traditions occurring in the 13th century AD, we can state that the ship or ships that were constructed with the Jaffa nails were at least influenced by the northern European ship construction tradition.

In the northern European tradition, scholarly typologies of ship/boat nails have relied on the morphological differences in nail heads, nail apexes, and shank cross sections. These nail shapes vary culturally, regionally, and chronologically (Bill, 1994, 55). The nails from Jaffa have round low heads, square shanks, and pointed turned apexes, meaning they fit Bill's ship nail type ACD (Fig. 15). This nail type is consistent with ship nails produced in England during this period. Nails with square cross-sections, such as those from the Jaffa examples, are used throughout the medieval period, but the assemblage after the end of the 12th century AD is characterized by the dominance of square-shanked nails (Bill, 1994, 60). It is noteworthy that Bill suggests this shift is connected to an economic change where boat nail production was transferred from the boat builder who only periodically made nails, to the blacksmith who possessed a permanent workshop. Square-shanked nails were easier to fashion, as they could be drawn quickly through a nail board without any further need of hammering for rounding. It is unclear whether steeling was more common in a permanent blacksmith's workshop than for the shipbuilder, but it is at least possible that the steel content of the nails from Jaffa could be related to professionalization in permanent workshops.

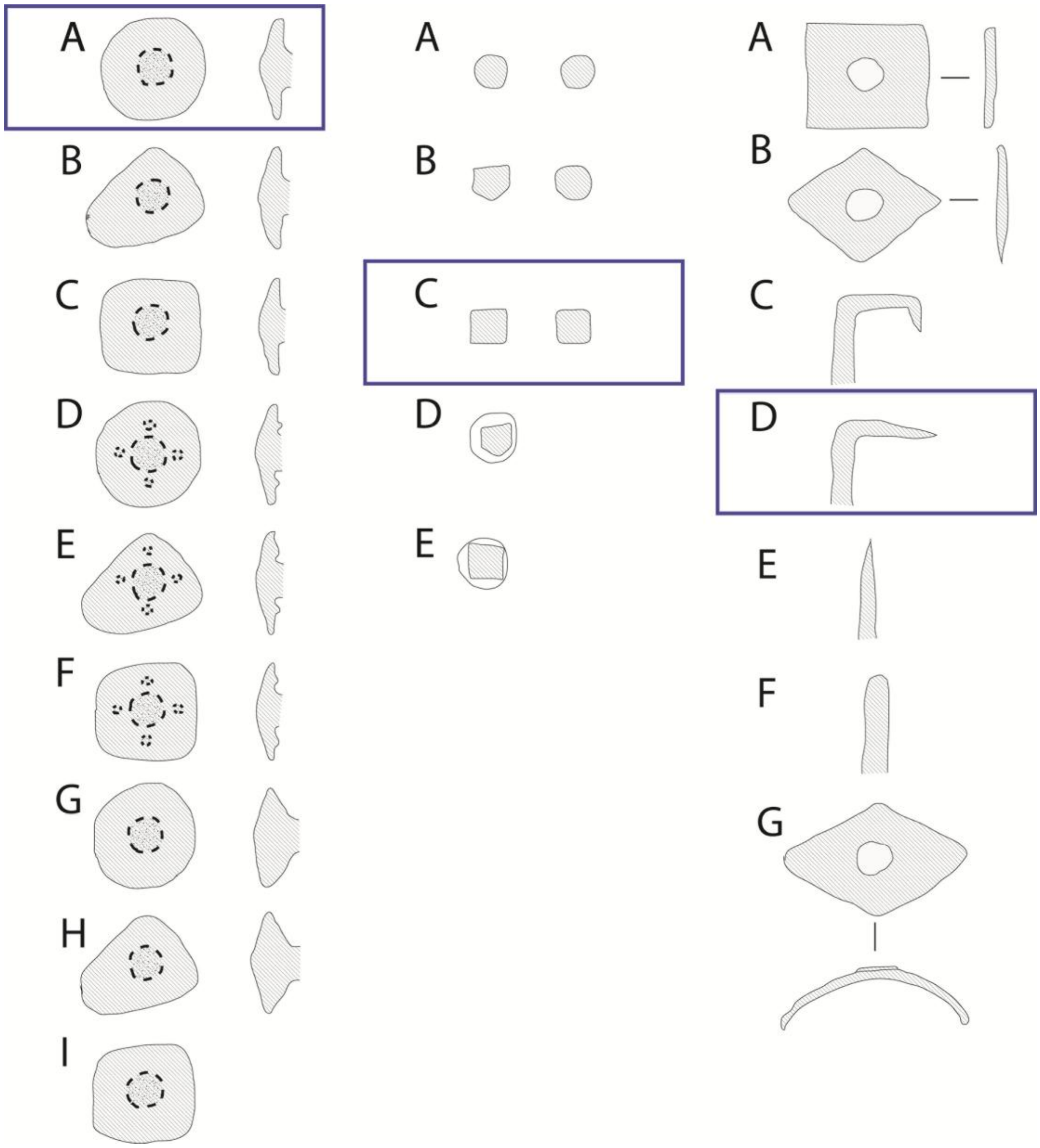

Figure 15. Ship/boat nail typology following Jan Bill's typology (reworked from Bill, 1994, figure 2, 57, see also Zori and Kaufman, 2017, figure 27.4, 417). The 3-part nail type of the Be'eri nails (ACD = round head, square shank, turned apex) is indicated by blue rectangles. The tripartite types are assigned based on head shape, shank cross-section, and the form of the apex.

Head shape	Shank cross section	Apex
A: round, low domed	A: round	A: rectangular rove
B: irregular, low domed	B: multisided irregular	B: rhomboid rove
C: square, low domed	C: square	C: hooked
D: A + points under head	D: B + plug	D: turned
E: B + points under head	E: C + plug	E: pointed
F: C + points under head		D: dull
G: A + conical towards shaft		G: curved rove
H: B + conical towards shaft		
I: C + conical towards shaft		

Iron nails of different types were of course used in the various Mediterranean ship traditions. They are apparent in iconographic depictions of medieval Mediterranean ships and have been recovered from excavated shipwrecks (cf. Bonino, 1978; Martin, 2001). Clench nails turned back into the wood are known in the Mediterranean ship tradition and were found as early as the 4th-century BC Kyrenia ship, where mortise-and-tenon planks were clench-nailed to the frame timbers (Steffy, 1985; 2001, 52). The 7th-century AD Yassiada Byzantine ship as well as the medieval Serce Limani ship from around 1025 both used mortise-and-tenon planking nailed with straight nails into the frame of the hull (Steffy, 2001, 55-6). In the Venetian Contarina I wreck from ca. 1300, which comes closest to the date of the Crusader nails from Jaffa, nails clenched under the keel were used to fasten floor timbers (Bonino, 1978, 15). These nails do not appear to us to match the nails recovered at Jaffa. However, the variability in ships and local ship traditions in the Mediterranean combined with the limited number of archaeologically recovered medieval Mediterranean ships means that the possibility of the Jaffa nails deriving from a ship in the Mediterranean tradition cannot be ruled out completely. It should be mentioned that the nails can most plausibly be identified as ship nails due to their typological correlations and coastal find context, but it cannot be wholly ruled out that they originated from non-maritime contexts.

The Jaffa nails are well within the nail length range for nails used in boat and ship construction. The clenching length of ship nails is the length of the nail between the nail head and the bend in the nail, which also indicates the thickness of the clenched wood. The five Jaffa nails have clenching lengths of 9 cm, 5 cm, >4 cm, 3.5 cm, and 2 cm (average clenching length is >4.7 cm). Clenching length is considerably variable even within the assemblage of a single ship/boat of the northern European tradition (for variability in length of ship/boat nail and rivet hardware see e.g. McCarthy, 1996). For instance, the 21.5-m long 10th century Ladby ship (Denmark) had planks measuring mostly ca. 2-2.5 cm in thickness (Sørensen, 2001). Especially small boat hardware can be very small, with examples of clench nails and clench bolts from medieval Iceland having clenching lengths below 1 cm, and with the longest generally clenching a length of less than 3 cm (see Zori, 2007; Roberts and Hreiðarsdóttir, 2013). Specifically, the ca. 7-m long boat from Litlu-Núpar (Iceland) had very slight planks ranging from 0.5 to 1.5 cm in thickness (Roberts and Hreiðarsdóttir, 2013). It is possible that the smaller of the clenched nails from Jaffa might not be from a ship's external hull planking, or that they might derive from a small boat of the type that is kept on ships as secondary vessels. However, we find it most likely that the longer of the Jaffa nails are from ships.

5. CONCLUSIONS

The conservation and reuse of ship parts and iron hardware is attested in the textual sources concerning Crusader Jaffa. According to Raymond d'Aguilers (1969, 147), the Genoese sailors who aided in the First Crusade siege of Jerusalem scuttled their ships to provide 'ropes, hammers, nails, axes, mattocks and hatchets,' which they used in the construction of siege towers. The Crusader nails recovered at Jaffa were extracted from a ship, but they do not appear to have been reused. The purpose for which the nails were intended is unclear. The character and distance of the recovery site from the sea makes it unlikely that the nails were removed and discarded during normal ship repair. The high-quality steel in the nails makes it interesting to consider whether the recyclers were specifically seeking steel, and the microstructural evidence does much to advance this supposition. The nails are likely derived from a context connected directly or indirectly to the shipbuilding traditions of the North Sea, particularly southern England.

The steeled nails from Jaffa further elucidate which techniques and processes were employed by Crusaders during this transitional time of direct versus indirect ferrous metallurgical reduction in the 13th century AD. In addition to hardness tests and quantitative compositional analyses using instrumentation especially calibrated for low carbon steels, further research of this corpus would benefit from investigating the slag inclusions to a greater degree.

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