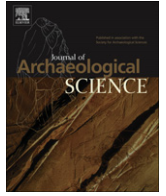




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New insights regarding the Akko 1 shipwreck: a metallurgic and petrographic investigation of the cannonballs

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ABSTRACT

The Akko 1 shipwreck constitutes the remains of a small Mediterranean naval vessel, discovered in Akko harbour, Israel, and excavated over three seasons between 2006 and 2008. Among the finds at the shipwreck site were eleven cannonballs. Two of them, a 9-pdr and a 24-pdr, were retrieved and studied using metallurgical and petrographic methods. The examination of the cast-iron was performed with optical microscopy, SEM–EDS, XRF and microhardness tests. The remains of the casting sand from within the voids in both cannonballs were studied by petrography. Combined with the archaeological evidence and the historical background, the metallurgical and petrographic testing may suggest that Akko 1 was a warship or an auxiliary naval vessel of similar size to, or slightly smaller than, sixth rate, and was in Akko harbour circa 1840.

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1. Introduction

1.1. Historical background

The city of Akko (Acre, St. Jean d'Acre) is located at the north end of Haifa Bay, in northern Israel. It is one of the oldest cities in Israel, with evidence of habitation since the Early Bronze Age (3300 BCE). It was connected to the sea by the Na'aman river (ancient Belus, see Josephus Flavius, *The Jewish War* 2.10.2). At sometime during the mid-first millennium BCE, the city was relocated to its present location on a promontory. Evidence of Phoenician harbour construction exists from this (Persian) period. Akko was conquered by Alexander the Great in 332 BCE and by the Arabs in 636 CE. In 1104 King Baldwin I and the Crusaders took Akko. It was conquered by Salāh ad-Dīn in 1187, and by Richard the Lionheart in 1191. The Mamelukes seized Akko in 1291 and destroyed the city and its harbour. The city was taken by the Ottomans in 1516. In the mid-eighteenth century the city and harbour were renovated by Daher al-Umar, its ruler from the mid-eighteenth century to 1775, and

after 1775 by Ahmed al-Jazzar Páshá, its governor until 1804 (Alderson, 1843; Cohen, 1973; Dichter, 1973, 2000; Dothan, 1976; Dothan, 1993; Makhoul and Johns, 1946; Raban, 1993; Rustum, 1926; Wilson, 1847).

Between the end of the eighteenth and the first half of the nineteenth centuries Akko was involved in three naval campaigns. Napoleon Bonaparte laid siege to the city on 19 March 1799. The besieged Turks, aided by a British squadron commanded by William Sidney Smith, fought back, and after 61 days of indecisive siege, the French retreated toward Egypt (Alderson, 1843, pp. 21–37; Anderson, 1952, pp. 372–373; La Jonquière, 1900, IV).

In 1831, Ibrahim Páshá, the son of Muhammad Ali—the ruler of Egypt, laid siege to Akko, aided by an Egyptian fleet composed of seven frigates, four corvettes, six brigs, a single bomb vessel and several transports. In December 1831, the Egyptian ships bombarded Akko heavily, but the engagement was not decisive. Gunfire from the city sank one gunboat and damaged the others. The Egyptian ships retreated to Haifa and later sailed back to Alexandria for repairs. However, the city was taken by the Egyptians six months later, on 27 May 1832 (Alderson, 1843, pp. 39–44; Durand-Viel, 1935, II, pp. 54–78; Rustum, 1926).

On 3 November 1840, a British–Turkish–Austrian fleet bombarded Akko. A shell hitting the main Egyptian arsenal resulted in an explosion which destroyed a section of the city. Akko was taken

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the following day (Alderson, 1843, pp. 46–48; Anderson, 1952, pp. 561–564; Durand-Viel, 1935, II, pp. 234–236).

In these naval operations, starting with Napoleon Bonaparte in 1799 through Ibrahim Páshá in 1831/2 and the conquest of the city in 1840, ships of various types, rates and classes from numerous western European or eastern Mediterranean fleets took part. From preliminary analyses of the archaeological data, it is believed that the Akko 1 shipwreck took part in one of these events.

1.2. The Akko 1 shipwreck

The Akko 1 shipwreck was excavated for three seasons (September 2006, June 2007 and June 2008), by an expedition headed by the Leon Recanati Institute for Maritime Studies at the University of Haifa. The wreck site (Fig. 1) is inside Akko harbour, 70 m north of 'The Tower of Flies', at a maximum depth of 4.0 m. The shipwreck remains were 23.0 m long from bow to the aft extremity, 4.38 m from the keel to the turn of the bilge, lying in a north-west to south-east direction. Only the lowest section of the port side of the hull has survived, including sections of the keel, false keel, bow timbers, hull planks, framing timbers, and ceiling planking, the majority of which were made from eastern Mediterranean hardwood (Cvikel and Kahanov, 2009, p. 40).

A variety of finds were discovered in the shipwreck including rigging elements and wooden artefacts, leather flasks, metal

objects, and ceramic ware. The majority of the metal objects were composed of cannonballs, lead bullets, muskets, brass cases and brass hooks. A total of eleven cannonballs were found, of which ten were inside the wreck (one of them is shown in Fig. 2) and one was found near the false keel (Fig. 3) under the bottom. The latter was 140.9 mm in diameter and 10.3 kg in weight, which suggests that it was a 24-pdr shot. Of the other cannonballs, one seems to be another 24-pdr, and the other shots were smaller, probably 9- and 12-pdrs (Cvikel and Kahanov, 2009, p. 51).

The surviving rigging elements found in the shipwreck: dead-eyes, blocks and sheaves, were thoroughly studied and compared with contemporary eighteenth and nineteenth century sources (Biddlecombe, 1848; Falconer, 1780; Lees, 1979; Lever, 1819; Marquardt, 1992; Rees, 1819–1820; Steel, 1794; Steel, 1805). The analysis of the rigging components suggests that Akko 1 was a three-masted sailing vessel carrying 14–22 guns. Reconstruction of the ship based on the hull remains suggests that she was about 28 m long. These assumptions of course require further research and proof.

Furthermore, the cannonballs, lead shot, muskets, and traces of fire on the hull timbers, provide abundant evidence for the ship being involved in warfare. Another possibility is that she could have been an auxiliary vessel shipping ammunition and armament to Akko. Using cannonballs as ballast was also known to have been practiced at the time (e.g. Hunter, 2004, p. 74; Lightley, 1976, pp. 311, 314–316).

1.3. Ships and armament

Starting in the eighteenth century, British navy warships were classified into six divisions according to the number of guns they carried. Only large ships of the first three rates carrying 100–120, 84–98 and 64–80 guns, respectively, were considered sufficiently powerful to be 'ships of the line'. Fourth, fifth and sixth rate ships were equipped with 50–60, 30–50 and 20–30 guns, respectively. Ships of the fifth and sixth rates were generally known as frigates. Smaller, unrated ships were defined by their purpose or rig, such as three-masted sloops, brigs, cutters, transports, bomb vessels and gunboats (Falconer, 1780, pp. 235–238; Kemp, 1976, p. 692; Lavery, 1987, 1989, pp. 120–123, pp. 40–57; Moore, 1926, pp. 4–5). In other navies, such as those of the Netherlands, France, Spain or Sweden, no systems of rating were developed (Glete, 1993, p. 82).

The early naval guns mounted on ships were either cast in bronze or made of wrought iron. Being expensive, bronze guns were gradually phased out of naval service in favour of cast iron. With improvement in the quality of gunpowder and cast-iron technology,

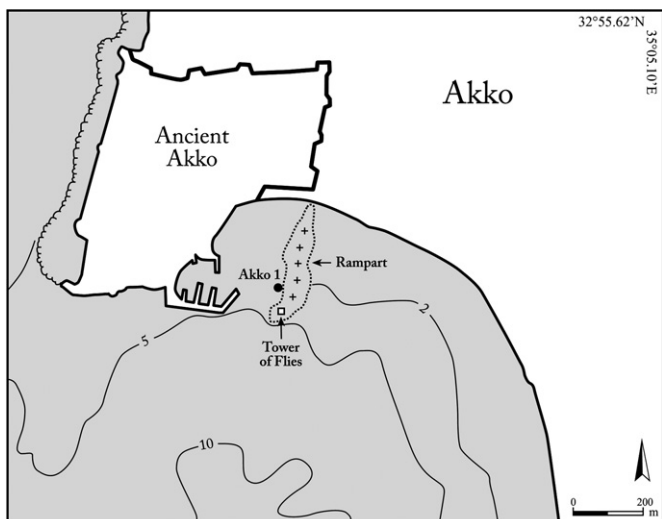
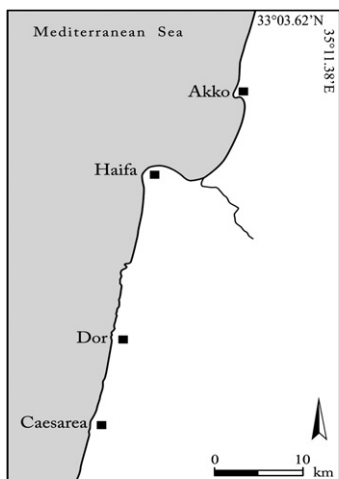


Fig. 1. Location of Akko and the Akko 1 wreck site.



Fig. 2. Akko 1, cannonball on frames.

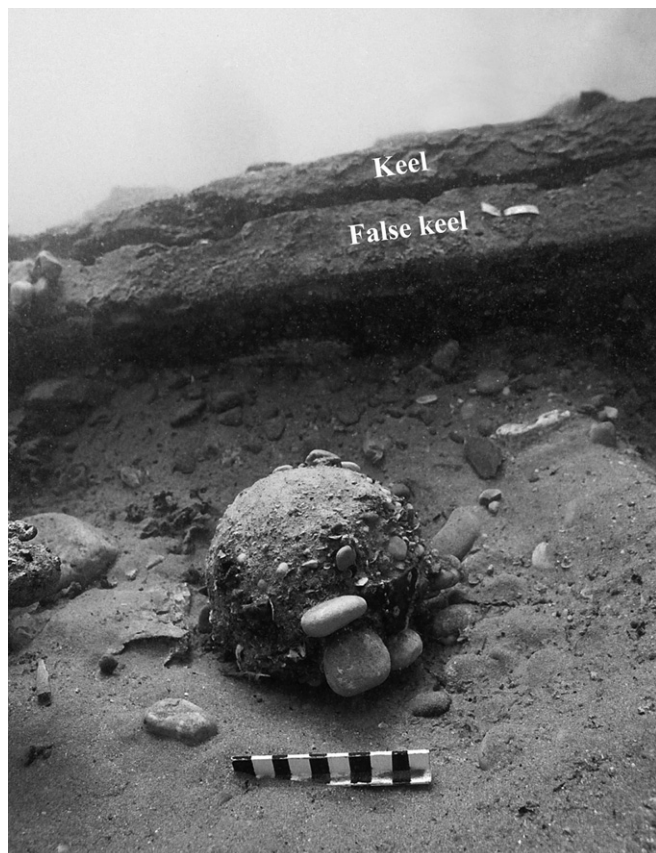


Fig. 3. The 24-pdr cannonball near the false keel.

guns were shortened, permitting larger calibres for the same weight. Guns were identified by the weight of the round shot (cannonballs) they fired, which were of various sizes in proportion to the calibre of the gun (Falconer, 1780, pp. 61–62; Glete, 1993, p. 26; Kemp, 1976, p. 363). The original shipboard guns were identical to land weapons, and it was not until the eighteenth century that they were fully designed for shipboard use (Lavery, 1984, p. 150). Stone shots were an ideal material for projectiles which had to be fired with small gunpowder charges. They were lighter, faster, and generated less stress on the gun than iron ones. However, as a result of the high cost of carving a round ball out of stone, as well as the improvement in the quality of gunpowder and iron casting technology, by the end of the sixteenth century, cast iron round shots had replaced the stone shots, and these were manufactured in clay moulds (Glete, 1993, p. 24; Hogg and Batchelor, 1978, p. 12; Lavery, 1987, p. 136).

In 1774 the carronade was developed by the Carron Iron Works in Scotland. It was a short, light gun, making use of a small propellant charge to fire a relatively heavy shot for a limited range. Due to the lower weight of the carronades, they impacted the ship's stability less. With low muzzle velocity they could create more damage upon impact. The carronade was introduced into service in the British Navy in 1779, though it was ignored by the French Navy until 1780. By 1804, iron carronades, similar to the British model, were in use on French ships. Carronades were not counted in the number of guns used for classifying a ship until the rating system was changed in 1816. Nevertheless, in unrated ships such as sloops and brigs, carronades were counted as the main armament from the start. The carronades went out of favour after the War of 1812 between Britain and the United States of America, but were still carried on ships as late as the 1840s (Hogg and Batchelor, 1978, pp. 21, 24; Boudriot, 1992, p. 99; Glete, 1993, p. 30; Kemp, 1976, pp.

363–364; Lavery, 1984, p. 151; Lavery, 1987, pp. 123–124; Lavery, 1989, pp. 82–84; Lyon, 1993, p. 3; Moore, 1926, p. 12, 18).

The French Navy adopted General Paixhans' shell (explosive) guns in 1837, and within a few years, British (1839), Russian, and other navies had also commenced using shell guns. Unlike long guns and carronades, shell guns were classified according to their bore calibre in inches (usually 8-inch). The shell, like the shot, was spherical and made of cast iron, but was hollow and filled with gunpowder. Although larger shell guns were made, the principal naval weapon until the Crimean War (1854–1856) and the introduction of the ironclad, remained the smooth bore cast-iron gun, firing a solid cast-iron round shot (Boudriot, 1992, 1993, pp. 116–119; 312; Hogg and Batchelor, 1978, pp. 28–30, 36; Moore, 1926, p. 19).

1.4. Suggested reconstruction of Akko 1 armament

As mentioned above, it is suggested that Akko 1 was 28 m long, three-masted, and carried between 14 and 22 guns. According to the rating system, she was of sixth rate or less (unrated). British and French ships of the sixth rate, carrying 24–30 guns, were about 35–42 m in length (Boudriot, 1993, pp. 156–157; Gardiner, 1992, pp. 16–17, 36–40; Moore, 1926, p. 7). The average spacing of guns along a gun deck was 10.5 feet per gun (Kahanov et al., 2008, p. 398). Thus, Akko 1 had carried less than 24 guns, perhaps 18.

The three cannonball types retrieved from the shipwreck were identified as 9-, 12-, and 24-pdrs. Were these shots part of the ship's ammunition or load (perhaps as ballast?) or was she hit by them? In principal, the lighter the ship the smaller the calibre of her main battery (Glete, 1993, p. 30). However, large calibre carronades, up to 32-pdrs, were also in use in ships of similar size in the relevant period (Lavery, 1987, 1989, p. 125, pp. 52–53; Boudriot, 1992, pp. 113–114). Therefore, Akko 1 could have carried 9-pdr guns, as well as 12- or 24-pdr carronades; for example, 16 12- or 24-pdr carronades and two 9-pdr long guns.

Nonetheless, any of the cannonballs found in the shipwreck theoretically could have been a shot that hit her. During the campaign of 1831/2, the largest ships in the Egyptian fleet were frigates of about 60 guns and carronades. The armament calibre was of 24-, 30- and 36-pdr (Bowring, 1998, pp. 152–153). The British fleet facing the walls of Akko in 1840 was carrying an armament comprised mainly of 24- and 32-pdr long guns, 18- and 32-pdr carronades, and 8- and 10-inch shell guns (Alderson, 1843, p. 62; Codrington, 1880, pp. 195–196; Lyon, 1993, e. g. pp. 106–107, 109–110, 114, 148). Different figures have been suggested in the historical sources for the exact number of guns mounted on the walls of Akko during this campaign. However, the types of guns are known: 18-, 24-, 32-pdr, and smaller calibre guns; howitzers; mortars; shell guns (8- and perhaps 10-inch, as well); and possibly a single 68-pdr carronade (Alderson, 1843, p. 61; Codrington, 1880, p. 493; Hunter, 1842, I, pp. 297–298).

At this stage of the research, all possibilities regarding the origin, use or purpose of the 9-, 12- and 24-pdr shots are open, but a clue to the wrecking date is proposed.

2. Background to research

2.1. Casting iron cannonballs

Cast iron is generically defined as a ferrous alloy containing between 2 and 4 wt. % carbon (C) and it usually contains between 0.5 and 3 wt. % silicon (Si) and smaller amounts of other elements such as phosphorus, sulphur, and manganese. The term derives from the technique by which the iron is manufactured. An increase in the amount of carbon lowers the melting point of the metal. Cast iron has good fluidity and castability but it tends to be brittle. The major

difference between gray cast iron and white cast iron is in the amount of silicon present in the alloy. Gray cast iron contains more than 1 wt. % Si and white cast iron contains less than 1 wt. % Si. Since silicon is a graphite stabilizing element, addition of more than 1 wt. % Si (gray cast iron) causes the carbon to precipitate as graphite flakes (black particles), surrounded by a matrix of pearlite (light phase), alternating thin layers of ferrite (a-BCC iron) and cementite (Fe_3C), also termed iron carbide (dark phase). The graphite flakes cause low ductility and strength, but have good machinability and wear resistance. Less than 1 wt. % Si (white cast iron) causes a precipitation of cementite particles rather than graphite. Because of the massive amount of cementite, white cast iron has good hardness and abrasion resistance but is very brittle.

The ideal geometry of a cannonball is a perfect sphere. However, it is quite exceptional to cast a cannonball of perfect geometry without any irregularities such as variations in microstructure or asymmetrical porosity and cavities, which consequently influence the accuracy of the cannonball during flight (Williams and Johnson, 2000). In order to reduce the porosity during the casting process, a feeder must be added and the casting material in the feeder should stay molten longer than the cast object. Shrinkage can then be reduced by feeding additional molten material into the cast object as it solidifies. In order to ensure that the material in the feeder remains fluid, the rate of heat transfer must be reduced, which is typically accomplished by adding a thermal sleeve around the feeder (Williams and Johnson, 2000).

The origin and period of manufacture of some ferrous alloys can be identified according to the history of technological development, distinguishing between different manufacturing technologies on the basis of their chemical characterization and microstructure. In 1839, Josiah Heath wrote a patent involving the addition of manganese to cast iron, which results in metal free of gas porosity and blow holes (Wiltzen and Wayman, 1999, p. 119; Wayman, 2000, p. 265). This technological evolution is most valuable as terminus post quem for the manufacture of the tested cast-iron cannonballs.

The presented study examined two of the three cast-iron cannonballs that were recovered from the Akko 1 shipwreck, a 9-pdr and a 24-pdr, and demonstrates interdisciplinary research, combining metallurgical and petrographic examinations in order to understand the story behind the Akko 1 shipwreck. Following the assertion that the 9-pdr and 24-pdr cannonballs are of unknown though different origin, in the next section the metallurgical and

petrographic tests performed will be described in order to determine the differences and/or similarities between the two.

3. Experimental methods and tests

Two sand mould cast-iron cannonballs (9-pdr and 24-pdr) were retrieved from the Akko 1 shipwreck (Fig. 4), and extensive metallographic and petrographic examinations were performed. The analysis of both cannonballs required the use of various scientific methods and sophisticated equipment including metallurgical and polarizing light microscopy, scanning electron microscope (SEM), with energy dispersive spectroscopy (EDS), X-Ray Fluorescence (XRF) spectrometry and microhardness tests.

In order to perform the metallographic examinations, samples were cut from the two cast-iron cannonballs using a dicing saw with a diamond wheel, transversely, creating strips that were then cut longitudinally into smaller pieces. Several samples were prepared from each cannonball. A rough polish was performed on the samples to eliminate the heat-affected zones created by the dicing saw. Then the roughly polished samples were mounted in Bakelite at a temperature of 180 °C and pressure of 20 bar. Surface preparation of the samples began by grinding with silicon carbide (SiC) papers (grade 240–600 grit), followed by polishing with 5–0.05 micron alumina pastes and a final polish with 0.05 micron colloidal silica polishing suspension paste. The samples were placed in an ultrasonic bath to remove any contamination, then cleaned with ethanol and dried. The samples were subsequently etched using Nital acid (97% alcohol and 3% HNO_3). After preparation, the samples were examined under a stereo microscope up to $\times 50$ magnification, and a metallographic optical microscope (ZEISS, AXIO Scope A.1) up to $\times 1000$ magnification. Following the metallographic examination, Vickers microhardness measurements were performed with 50 grf load using a Future-Tech FM-700e microhardness tester. In places where substantially different microstructural constituents were present, multiple hardness readings were taken.

ESEM (Environmental Scanning Electron Microscope) examination including EDS analysis was performed for both cannonballs before and after etching. The morphologies of the samples were characterized by an FEI Quanta 200FEG ESEM in high vacuum mode, using the Everhart–Thonley Secondary Electron (SE) detector. The chemical element composition was analyzed by EDS using Si(Li) liquid cooled Oxford X-ray detector.

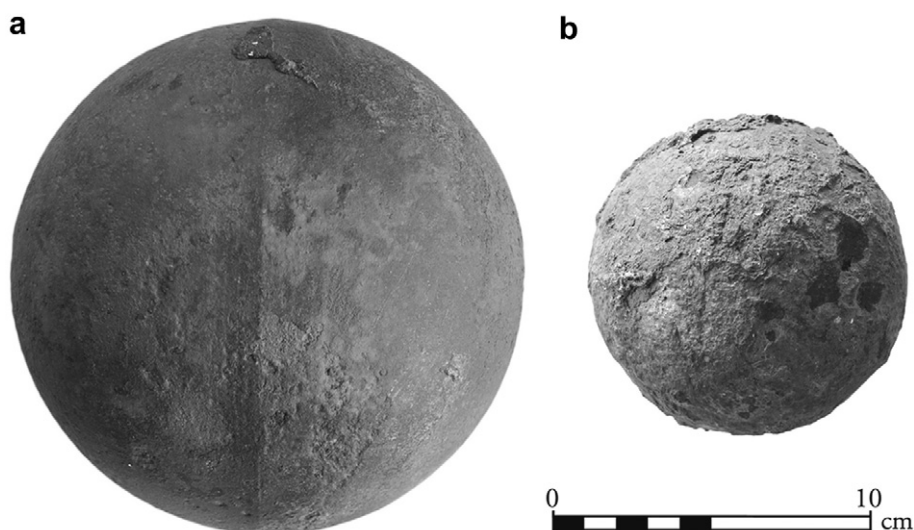


Fig. 4. Images of the 24-pdr (a) and 9-pdr (b) cannonballs after cleaning of the marine encrustation.

Chemical analysis was also performed on polished sections from both cannonballs by using a Thermo Scientific Niton XLt-900 GOLDD handheld XRF. This specific apparatus includes a 50 kV X-ray tube with a Geometrically Optimized Large Area Drift Detector (GOLDD), 80 MHz real-time digital signal processing, and dual embedded processors for computation, data storage, live video processing, and communication. The irradiation area is circular, 8 mm in diameter, and measurements are taken by means of the characteristic secondary X-rays emitted from a material as it is bombarded with high-energy X-rays.

Petrographic examination was performed on sand residues collected from internal cavities found during the cutting of the two cannonballs for the metallographic sample preparation. The sand from both cannonballs was analyzed using polarized light microscopy. For the petrographic investigation, the cavities found in the cannonballs after the preliminary dicing, were drilled, and the sediment trapped within them was collected. The sediment was dried in an oven at 80 °C for 24 h, and then the metallic grit (resulting from the drilling) was removed with the aid of a magnet. Sample preparation followed the method developed by Goren for the preparation of thin sections for petrographic analyses from small amounts of unconsolidated sediments (Goren et al., 2004, pp. 11–12). The samples were set in improvised moulds made of small rounded polyethylene test tube cups. The cups with the samples were then put into a desiccator, where they were impregnated with Buehler Epo-Thin low viscosity epoxy resin under vacuum conditions. After curing, the resulting pellets were used for the preparation of standard thin-sections and subjected to routine petrologic examination under a Zeiss Axiolab-Pol polarizing microscope using $\times 50$ – $\times 400$ magnifications.

4. Results

The optical metallographic examination of the 24-pdr cannonball revealed a corrosion layer at the surface of the cannonball. Beneath the corrosion surface, a dendritic cast iron microstructure was observed, as shown in Fig. 5a. Different zones of the 24-pdr cannonball demonstrated different structures including gray cast, white cast and graphite precipitates resulting from variation of both the cooling rate and the local chemical composition, mostly carbon content, at each location. The 24-pdr cannonball dendritic microstructure near the surface is made of gray cast iron including pearlite phase (gray) and graphite flakes (black worms), while the microstructure at the centre of the 24-pdr is white cast iron including cementite precipitates (dark gray) surrounded by pearlite matrix. The optical metallographic examination of the 9-pdr cannonball revealed a corrosion layer at the surface as well. Beneath this corrosion layer, white cast-iron was observed, as shown in Fig. 5b. Unlike the larger 24-pdr cannonball, the structural modification in the 9-pdr is uniform dendritic microstructure of only white cast iron, including cementite plates (bright) in ledeburite matrix, but with no evidence of gray cast iron occurrences.

The ESEM examination was performed before and after polishing and etching. The 24-pdr cannonball was examined in several locations in order to clarify the different phases observed under optical microscopy. In the centre of the 24-pdr cannonball, Fig. 6, the existence of white cast iron was observed. The EDS analysis of the cast iron, shown in Fig. 6, revealed the presence of iron (93.7 wt. %), carbon (4.8 wt. %), manganese (0.8 wt. %) and phosphorus (0.7 wt. %), which are typical elements in white cast iron. No silicon presence was observed here. At the places where the presence of phosphorus was observed, the surface was brighter. Another EDS examination, which was performed near the centre of the 24-pdr cannonball, revealed the presence of iron (95.4 wt. %), carbon (3.8 wt. %), and manganese (0.8 wt. %), which are also typical of

white cast iron. Near the edge of the 24-pdr cannonball, seen in Fig. 7, existence of a gray cast iron was observed as graphite flakes or worms (dark areas) became visible. The EDS analysis of the cast iron shown in Fig. 7 revealed the presence of iron (97.4 wt. %), carbon (1.4 wt. %) and silicon (1.2 wt. %), which are typical of gray cast iron. Another EDS examination was performed on a dark worm shown in Fig. 7b. It revealed presence of carbon (89.8 wt. %) and iron (10.2 wt. %) which indicates that indeed the flakes are made of graphite. Different kinds of corrosion products were observed in various areas of the 24-pdr cannonball. A SEM micrographs and EDS analysis of a cavity in the bulk of the 24-pdr cannonball (white cast iron area) before grinding, polishing and etching, revealed akaganeite ($b\text{-FeOOH}(\text{Cl}_x)$), which is a crystalline structure and a most common corrosion product of iron in the marine medium (Gil et al., 2003). The chloride ions are necessary materials for akaganeite formation and stabilization. The SEM view of the surface of the cannonball (near the gray cast iron area) and EDS analysis revealed uniform corrosion. The structure of the 9-pdr cannonball was identified as being of white cast iron, as shown in Fig. 8. The EDS analysis of the 9-pdr cannonball micrographs shown in Fig. 8 revealed the presence of iron (95.4 wt. %), carbon (3.8 wt. %) and manganese (0.8 wt. %).

XRF examination of samples extracted from the non-corroded section of the 24-pdr cannonball revealed the presence of iron (84.4 wt. %), silicon (0.9 wt. %), manganese (0.5 wt. %) and

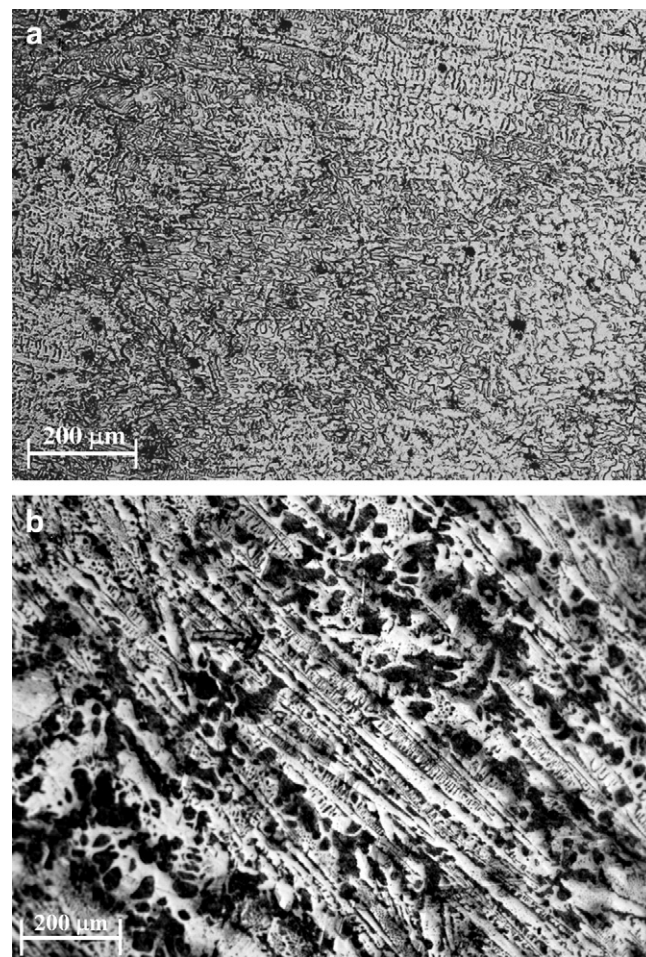


Fig. 5. Optical microscopy images of the metallographic sample of the bulk of the cannonball after grinding, polishing and etching shows: (a) a dendritic pattern in the 24-pdr cannonball, (b) a pearlite dendritic pattern (dark) observed in the 9-pdr cannonball.

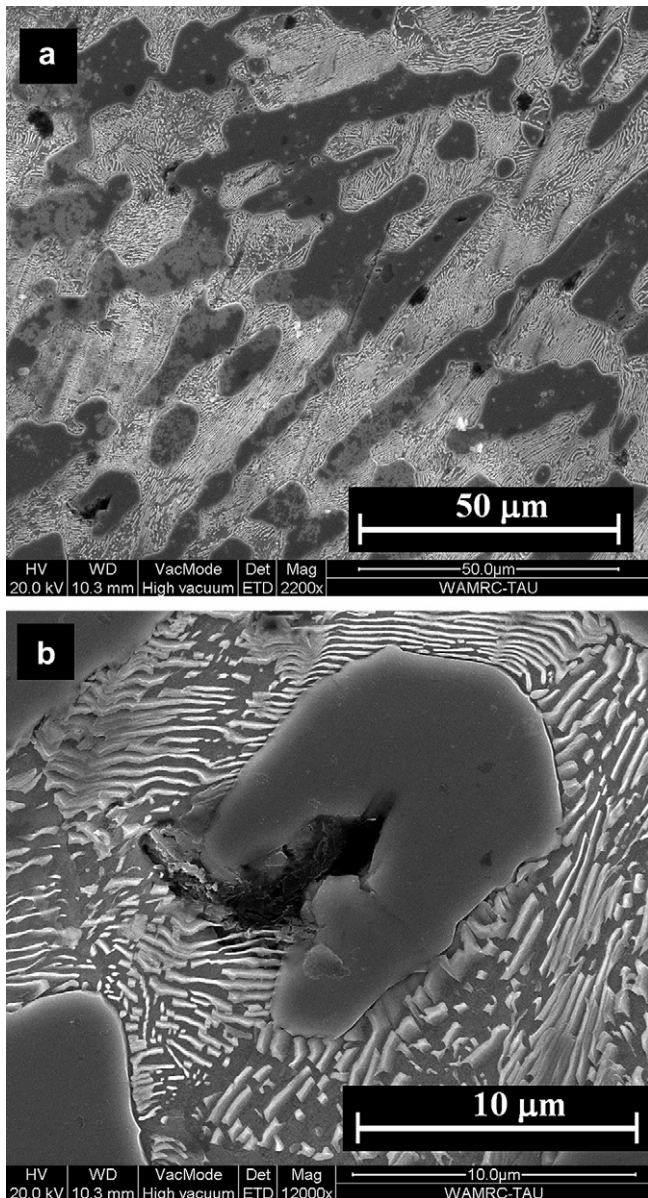


Fig. 6. SEM micrographs of the 24-pdr cannonball in the bulk of the cannonball after grinding, polishing and etching: (a) SEM micrograph of the white cast-iron, (b) enlargement of a typical area including a cementite precipitate surrounded by pearlite matrix.

phosphorus (0.6 wt. %). As no light elements such as carbon and oxygen can be observed by the XRF apparatus, they are included in the missing 13.6 wt. % 'balance'. XRF examination of the non-corroded section of the 9-pdr cannonball, revealed the presence of iron (85.5 wt. %), silicon (0.9 wt. %), manganese (0.5 wt. %) and phosphorus (0.6 wt. %). Since no light elements above Mg can be observed with this instrument, they are included in the missing 12.6 wt. % of the 'balance'.

Microhardness measurements made for the 24-pdr cannonball revealed four typical values: the characteristic microhardness of the corrosion front along the surface (313.3 ± 52 HV), characteristic gray cast iron microhardness 5 mm beneath the surface (481.4 ± 208.5 HV), and characteristic microhardness of white cast iron in the bulk of the cannonball (564.2 ± 346.4 HV). The fluctuations of the microhardness measurements are most likely due to the different phases that appear at every location. Microhardness measurement results for the 9-pdr cannonball

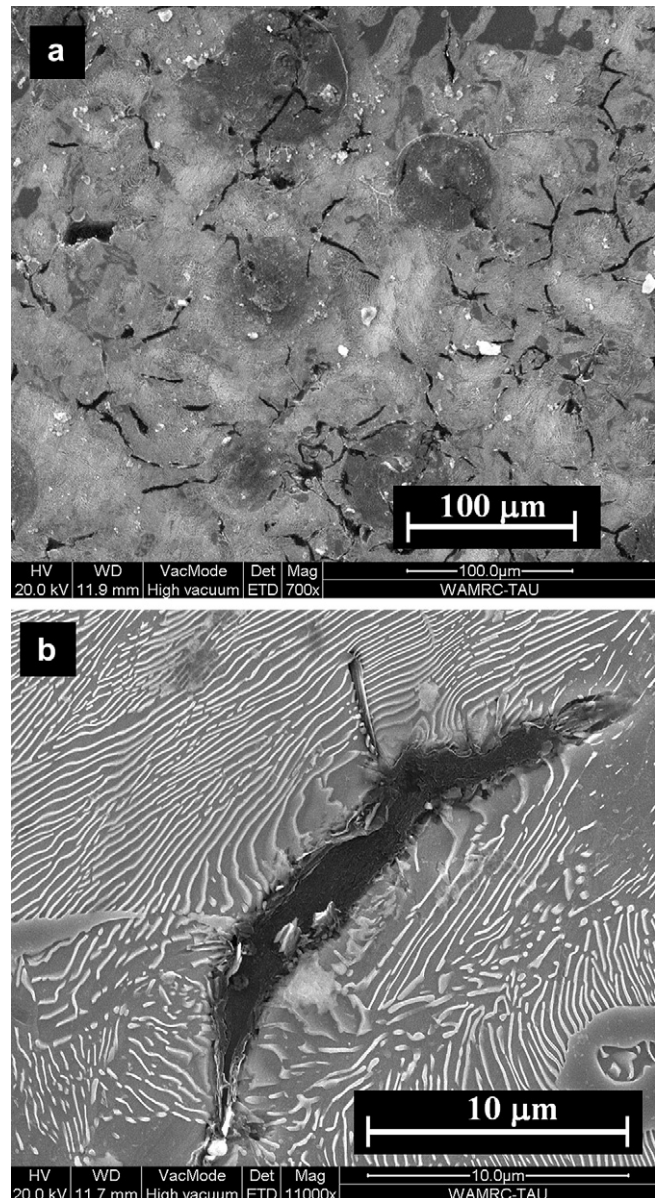


Fig. 7. SEM micrographs of the 24-pdr cannonball in the bulk of the cannonball after grinding, polishing and etching: (a) SEM micrograph of gray cast-iron, (b) enlargement of a typical area containing graphite flake (black area).

revealed three typical values found along its cross-section: characteristic microhardness of the corrosion front along the surface (684.6 ± 160.3 HV), characteristic white cast iron microhardness 5 mm beneath the surface (648.8 ± 82.3 HV) and characteristic white cast iron microhardness at the bulk of the cannonball (774.4 ± 205.7 HV). These microhardness values, which are typical of white and gray cast iron, indicate the presence of those phases.

Fig. 9a and b show the images received from the petrographic samples of sand from the bubble-shaped voids within the 24-pdr and the 9-pdr cannonballs, respectively. The sediments analyzed from the pores in the shot could not have come from the sea-floor environment since they were taken from holes located near the centre of the 24-pdr and 9-pdr cannonballs, in places where no presence of corrosion products was observed. Interior pores with casting sand present are common in sand cast objects (Williams and Johnson, 2000).

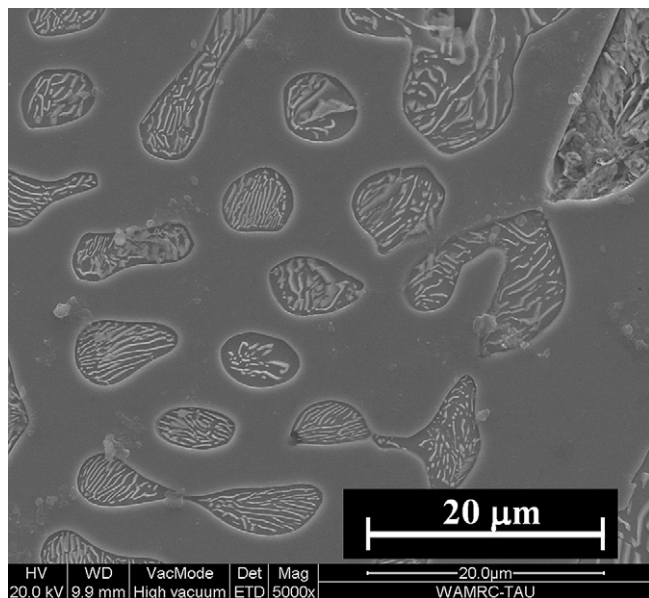


Fig. 8. SEM micrographs of the 9-pdr cannonball examination in the bulk of the cannonball after grinding, polishing and etching revealed white cast iron.

Most of the surface is constructed of grits of opaques or those which are nearly so, indicating iron oxide (corrosion) that was not completely removed by the magnet prior to the thin section preparation. The remaining sand, which most likely originated from the sand-cast deposit, includes angular, sand-sized fragments and singular crystal grains derived from crushed quartz (in the case of the 24-pdr), and felsic plutonic igneous rocks (in the case of the 9-pdr). While the sand from the 24-pdr, seen in Fig. 9a, is quartzitic, the 9-pdr yielded sand dominated by rock fragments containing quartz and riebeckite (pleochroic in blue under the microscope, see Fig. 9b). This most likely indicates a source area for the sand, where riebeckite granite was common. Since riebeckite, a sodium-iron silicate mineral $[\text{Na}_2\text{Fe}^{2+}_3\text{Fe}^{3+}_2\text{Si}_8\text{O}_{22}(\text{OH})_2]$, is not common in the eastern Mediterranean, this result is significant. It may also hint at some difference between the two examined cannonballs in terms of their location of manufacture.

5. Discussion

The Akko 1 shipwreck was found inside Akko harbour at a maximum water depth of 4.0 m. The ship was reconstructed based on the hull remains, the surviving rigging elements and historical data relating to ships of the period. It is suggested that she was a 28 m long, three-masted ship, armed with about 18 guns, some of which could have been carronades. The size of the cannonballs can be attributed to a 9-pdr long gun or 12-, 24-pdr carronades. The ship components were made mainly of eastern Mediterranean hardwood.

As many finds related to warfare activities such as cannonballs, muskets, and lead shots were found at the shipwreck site, it may be suggested that Akko 1 had a naval affiliation, being a small warship or an armed auxiliary naval vessel. Since only round iron shot were found in the shipwreck, and no explosive shells, it thus might indicate a date earlier than about 1839. This may also suggest that the original ship did not carry shell guns.

It is clear from Figs. 5–9 and from the microhardness results that the two cannonballs retrieved from the shipwreck were made of different cast iron. While the 24-pdr cannonball is non-uniform: mainly white cast iron at the bulk and gray cast iron at the parts

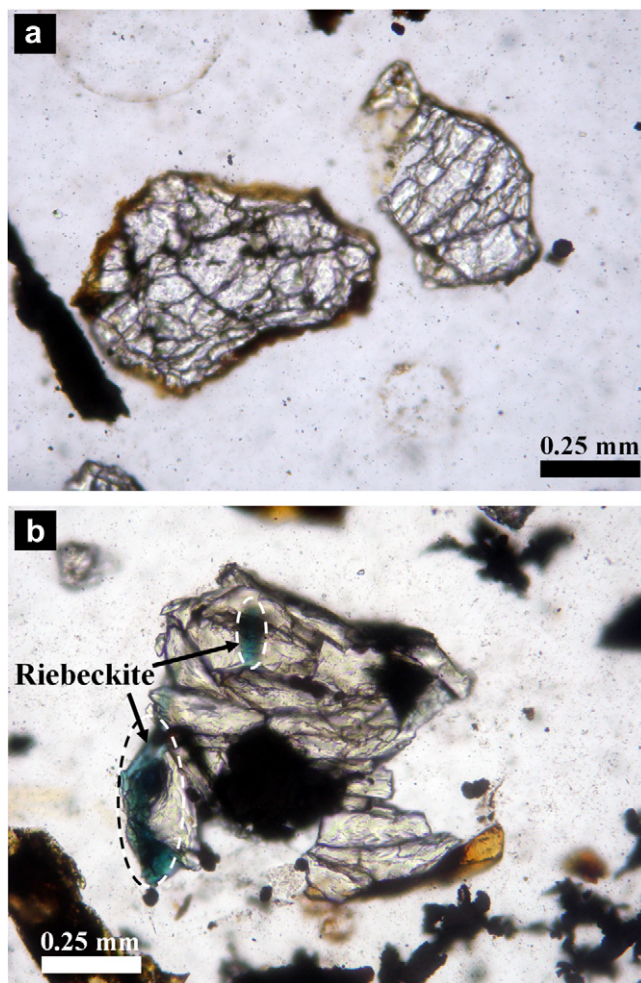


Fig. 9. Petrographic examination: (a) sand found in the 24-pdr cannonball, (b) sand found in the 9-pdr cannonball including an angular coarse particle containing riebeckite (marked), quartz, and opaque minerals (all in plain polarized light).

close to the surface, the 9-pdr cannonball is white cast iron and is more uniform in its structure.

The chemical composition of the iron used in casting the cannonballs provides a clue to the date of their manufacturing. The high concentration of manganese is crucial and, at sufficient levels, may suggest its intentional addition (Wiltzen and Wayman, 1999; Wayman, 2000, p. 265). The fact that both cannonballs have high concentrations of manganese (>0.5 wt.%) may indicate a post-1839 manufacture date. This result is highly important as it narrows the time frame in which the ship operated in the vicinity of Akko. Future work will include a detailed full quantitative analysis of the composition of the cast iron in different locations of the cannonballs including analysis of the corrosion products on the surface of the cannonballs.

The complementary results of the petrographic and the EDS analyses indicate that while the sand derived from internal cavities of the 24-pdr cannonball can be interpreted as crushed quartz, which technically could be derived from any source. The sand inside the 9-pdr cannonball contains either arkosic clasts from a source area dominated by riebeckite granite, or crushed and sieved particles from the same type of rock. Indeed, sand for sand casting can be theoretically imported to the manufacturing workshop from any foreign location. On the other hand, since the presence of riebeckite in the sand has no apparent technical benefit, it may be suggested that it reflects an opportunistic use of the

nearby lithology around the production area. If this is indeed the case, the workshop of the 9-pdr cannonball should be sought in an area where felsic igneous rocks containing riebeckite are found. Hence, the riebeckite may indicate the location of its manufacture, as the nearest outcrops of riebeckite granite are found in several locations in Egypt: in the Eastern desert, the Western Desert (El-Baz, 1984, pp. 363–364), and in southern Sinai Peninsula (Ali et al., 2009). This observation narrows, and may even identify the location of manufacture of the 9-pdr cannonball, especially since, during Muhammad Ali's reign, ammunition, gunpowder and arms began to be locally manufactured in Egypt. In 1815 a gunpowder factory was established on Roda Island, and an iron foundry was established in the citadel of Cairo, where three to four cast-iron guns were manufactured per month. There was also a munitions factory for the production of cannonballs, gunpowder, and bullets (Bowring, 1998, pp. 121–122; Marsot Al-Sayyid, 1984, pp. 165–166).

During the naval campaign for Akko in 1840, the town was bombarded. Its main powder magazine suffered a direct hit, which resulted in a massive explosion. The town was heavily damaged and her fortifications were destroyed. The place was left in ruin the following years: 'Everything stands and lies about as though the enemy had departed but yesterday'. More than ten years after the campaign, Akko was still under repairs (Pfeiffer, 1852, pp. 118–119; Wilson, 1847, pp. 233–234). Considering the naval context of Akko 1 shipwreck, and the fact that no other naval campaign took place in Akko's vicinity after 1840, combined with the metallurgic and petrographic aspects, it is suggested that the Akko 1 shipwreck could have taken part in the battle of 1840 and sank. However, being an auxiliary vessel that entered Akko harbour with ammunition and supply a short while earlier or even later than 1840 is no less logical. The 1840 dating or earlier reinforces the assumption that it was a ship friendly to the Egyptian forces controlling Akko at that time (Cvikel and Kahanov, 2009, p. 56).

6. Conclusions

Based on the experimental results combined with the archaeological and historical background, it may be suggested that Akko 1 was a warship or an armed auxiliary naval vessel of a size similar to, or slightly smaller than sixth rate, and was in Akko harbour about 1840. Petrographic analysis of the 9-pdr cannonball might offer a possible clue to the location of its manufacture, probably in Egypt.

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