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Identification of Fazael 2 (4000–3900 BCE) as first lost wax casting workshop in the Chalcolithic Southern Levant

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Abstract

Apart from many lost wax cast metal fragments, crucible fragments and several heated sediment nodules were found at the Chalcolithic site Fazael 2 (central Jordan Valley). Petrographic investigations on the heated sediment nodules revealed many features characteristic of the Chalcolithic Southern Levantine lost wax casting moulds. Heating temperatures were assessed using infrared spectroscopy, showing that casting did not vitrify the clay fraction in the moulds. Consequently, Fazael is the first identified Chalcolithic Southern Levant production site for lost wax cast metal items. These findings confirm the existence of a metallurgical tradition with lost wax casting in the Jordan Valley parallel to the unalloyed copper metallurgy in the Northern Negev. Moreover, crucibles and heated sediment nodules are made of local ferruginous loess, a material not mentioned in previous studies on lost wax casting mould fragments. Therefore, the existence of more than one such production site must be assumed.

Keywords Crucible, Mould, Lost wax casting, Petrography, Metallurgy, Chalcolithic, Southern Levant, Fazael

Introduction

The metallurgy of the Late Chalcolithic Southern Levant (4500 to 3800 BCE) is most famous for its intricate and large lost wax cast objects made of polymetallic copper alloys rich in arsenic and antimony. Earlier finds of lost wax cast items are restricted to Varna (Bulgaria) on the West Coast of the Black Sea, where gold was cast in this technique to a couple of personal ornaments such as beads and bracelets around the mid-5th millennium BCE [1, 2]. In addition, small lost wax cast spoke wheel-shaped items made of unalloyed copper were found in Mehrgarh (Pakistan) but can be only very broadly dated to 4500 to 3600 BCE [3]. Compared with the items found on these sites, the lost wax cast items in the Chalcolithic Southern Levant are special in multiple aspects: They are evidence for a highly innovative and isolated technology in Western Asia, which disappears at the end of the Chalcolithic [4]. They use an alloy, which was not used elsewhere in West Asia at this time or any time after [5]. And they are huge compared to the items in the other regions, with some objects being longer than 50 cm and the majority weighing more than 100 g per items, some even more than 500 g [6].

The largest assemblage of such objects is the Nahal Mishmar Hoard, which was found in a cave close to the Dead Sea and features, among others, more than 300 unique lost wax cast items such as mace heads, standards, crowns or vessels [6]. In contrast to the contemporary well-understood pure copper technology confined to the Northern Negev, which smelted ore from Faynan to copper and cast it to tool-shaped objects in open moulds

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[7–13], the metallurgical process of the polymetallic copper alloys and the lost wax casting process remains enigmatic in most aspects due to the seeming absence of production sites. Consequently, current knowledge was solely obtained by investigating the metal items, mould remains adhering to them and the ceramic or lithic cores in many of the mace heads. These studies show that the metals were produced from Anatolian or Caucasian ores [14]. However, petrographical investigations of the core material and mould remains revealed that they all are made of Southern Levantine materials [15–17], indicating that at least casting was carried out in the Southern Levant. Furthermore, the mould remains revealed a multi-layered mould design with pastes prepared from different clays, carbonaceous sand and vegetal material, or plaster mixed with animal dung and basalt split [15, 16]. Based on the outcrop location of the clays, the Jordan Valley and En Gedi were suggested as potential production sites (Fig. 1) [15].

Recently, Rosenberg et al. [18] presented a large assemblage of lost wax cast polymetallic copper alloy objects and fragments found in Fazael in the central Jordan Valley. The site also yielded several crucible fragments. The presence of a lost wax casting production site in Fazael was suggested because of the co-occurrence of lost wax cast metal fragments and crucible fragments [18]. Furnaces and other evidence for metallurgical activities such as slag remain to be found [18].

To further our understanding of the metallurgical process at Fazael and provide additional evidence for the discussion of whether Fazael was a lost wax casting production site, the ceramic material presented by Rosenberg et al. [18] and ceramic material from a later excavation season was investigated by petrography and with a scanning electron microscope equipped with an energy dispersive X-ray spectrometer (SEM-EDX). The results suggest that Fazael, specifically the sub-site Fazael 2, is indeed a lost wax casting workshop, making it the first ever found. Finally, the implications of this result for our understanding of the Chalcolithic metallurgy in the Southern Levant are discussed.

Archaeological background of Fazael

Fazael is a multi-site cluster along the northern riverbank of the Wadi Fazael (Fig. 1). The oldest site and the site furthest west is Fazael 1, a multi-strata settlement with

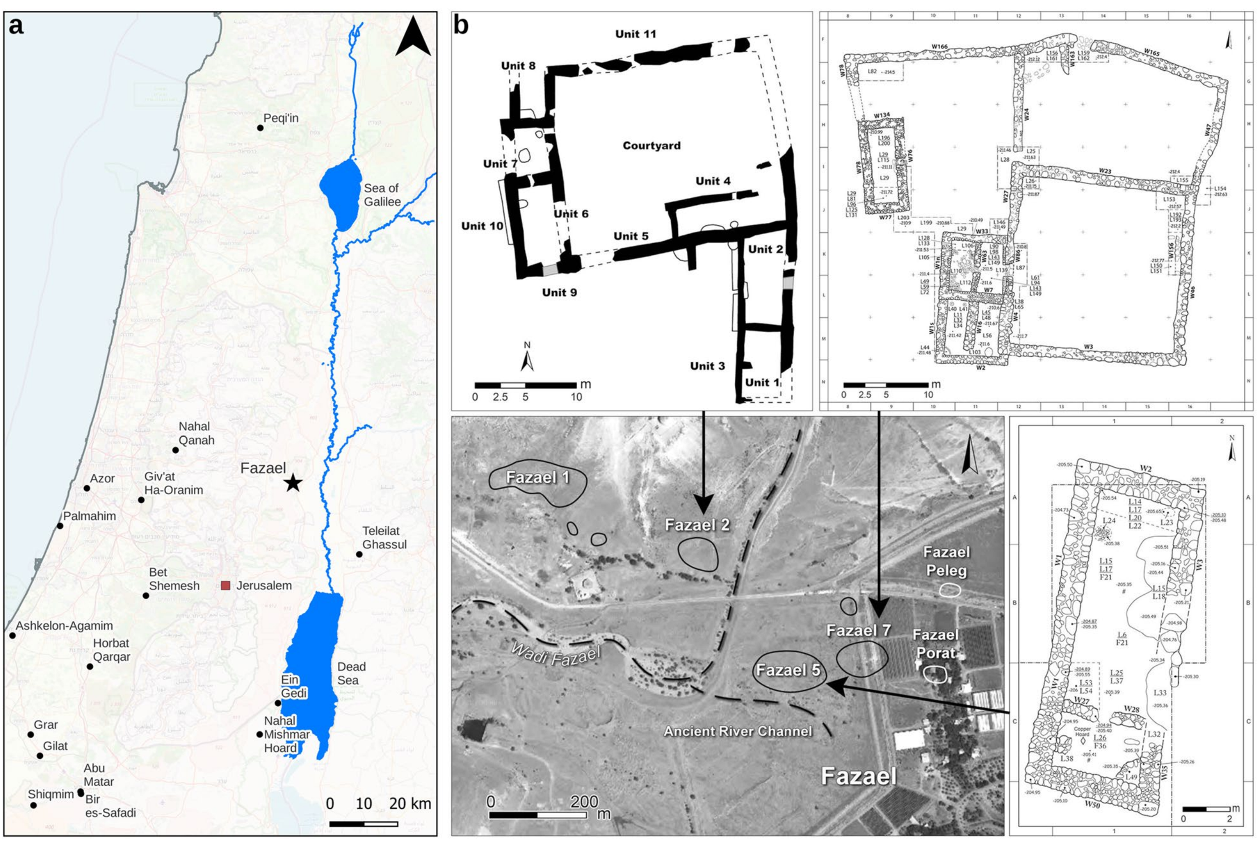

Fig. 1 **a** Map showing the location of Fazael (base map: openstreetmap.org) and **b** satellite image with the location of the Fazael sub-sites and the plans of the excavated buildings (Fig. 2 in Rosenberg et al. [18], licensed under CC-BY 4.0)

material culture typical for the Chalcolithic Southern Levant [19]. Settlement activities shift east towards the end of the Chalcolithic, where the areas Fazael 2 [20], 5 [21], 7 [22], and Porath 1985 excavation [23] were excavated. All of them are broad room houses connected to courtyards with the same general stratigraphy of three strata and the same material culture. Stratum II is the main settlement phase in all three sites (Fazael 2, 5, and 7). Radiometric dates of charcoal from this stratum at Fazael 2 yielded a date between 4000 and 3900 BCE, i.e. at the very end of the Chalcolithic. It could not be corrected for the old wood effect and might even be a bit younger [20].

While all of the Fazael buildings are larger than usual Chalcolithic houses, the four-roomed building of Fazael 7 with its courtyards is currently the largest known Chalcolithic building in this region [22]. At all sites, the outer and courtyard walls are made of two rows of large stones (up to 1 m) infilled with gravel and earth. Remains of clay bricks were found on top of some of them in Fazael 2 [20]. Walls of smaller stones divide most of the rooms into smaller rooms. Within these rooms, one phase with careful building maintenance was identified in Fazael 7 [22], and in Fazael 5, one floor was found in each room [21]. In contrast, Fazael 2 yielded several floors per room, indicating a prolonged settlement period [20]. One of the rooms at Fazael 2 contained two infant burials [24].

The very late date is supported by the material culture of all three sites which is best described as an incomplete assemblage of the later phase of the Late Chalcolithic *sensu* Gilead [25]. For example, no churns or fenestrated bowls were found and only one cornet tip was present (in Fazael 2). Beside V-shaped bowls, S-shaped bowls were found, which became widespread mainly in the Early Bronze Age. Similarly, the typical Chalcolithic bi-facial flint tools are almost absent while Canaanean Blades were found in all sites [20–22]. Canaanean Blades are characteristic of the Early Bronze Age but also occur in other sites dating to the end of the Chalcolithic [26]. Similarly, mortars are more abundant than grinding stones, setting Fazael 2, 5, and 7 apart from other Chalcolithic sites, including Fazael 1 [27].

The large number of metal objects found at Fazael is outstanding. They are most abundant in Fazael 2 (34 items), followed by Fazael 7 (14 items) and Fazael 5 (4 items), but this might be a result of the different excavation activities, ranging from a very large extent in Fazael 2 to a smaller excavated area in Fazael 7 and only probes in Fazael 5. Most of the metal items are fragments of standards, crowns, mace heads, and chisels. Moreover, excavations uncovered complete chisels, a mace head placed in a wall at Fazael 7, and, a head-shaped standard at Fazael 5, into which's shaft hole an awl, a chisel, and a third object were shoved [18, 21, 22]. The metal items in Fazael 2 and Fazael 7 are scattered over the entire site without any apparent pattern. Besides the characteristic polymetallic copper alloys with high Sb and As levels, preliminary pXRF analyses of many objects identified an unusually high Pb content of >0.5 wt%, and one object seems to be made of a copper enriched in Pb and Bi [18].

In addition to the metal objects, Fazael 2 yielded several crucible fragments, as indicated by the corroded metal prills attached to some of them and the bloated rims (Fig. 2). Their co-occurrence with the many metal fragments leads Rosenberg et al. [18] to suggest pyrometallurgical processing of polymetallic copper alloys in Fazael 2, probably to recycle outdated or broken cultic metal objects.

Material

All of the analysed material was found in Fazael 2. Six fragments of crucibles and burnt glazed sediments were sampled for petrography, and four for infrared spectroscopy (Table 1). Five of them were previously reported [18]. F225a is newly reported here. It is a piece of hardened sediment with an irregular shape and one potentially smoothed side (Fig. 3a) with the same find tag as F225.

Pieces of what appear to be baked or heated sediment nodules were excavated in 2020 in the eastern rooms of the broad house at Fazael 2. They are up to 4 cm in size, rounded, and brittle. Some of them broke in the field and exposed a reddish or black ceramic-like material of varying colour (Fig. 4). They were taken from the excavation directly to the lab without further treatment. Nine of them were sampled for petrography and six for infrared spectroscopy. F2-Y39, F2-Y42, F2-Y50, F2-Y52, and F2-Y55 were found in the same spot, making it likely that they belong to the same deposition event.

Methods

The crucible fragments and the burnt glazed sediments were carefully inspected with a stereomicroscope to identify any adhering slag remains or copper prills. The fragments were subsequently sectioned and the sections were embedded in epoxy resin under a vacuum. The baked sediment nodules were partially immersed in epoxy resin under a vacuum before cutting to increase their mechanical stability. Petrographic thin sections were prepared from all samples according to standard procedures and analysed with a petrographic microscope. The chemical composition of isotropic amorphous inclusions in F2-Y55 was measured with the SEM-EDX FEI Quanta 200 of the Ilse-Katz-Institute for Nanoscale Science & Technology, Ben-Gurion University of the Negev, Beer Sheva (Israel). It was operated at

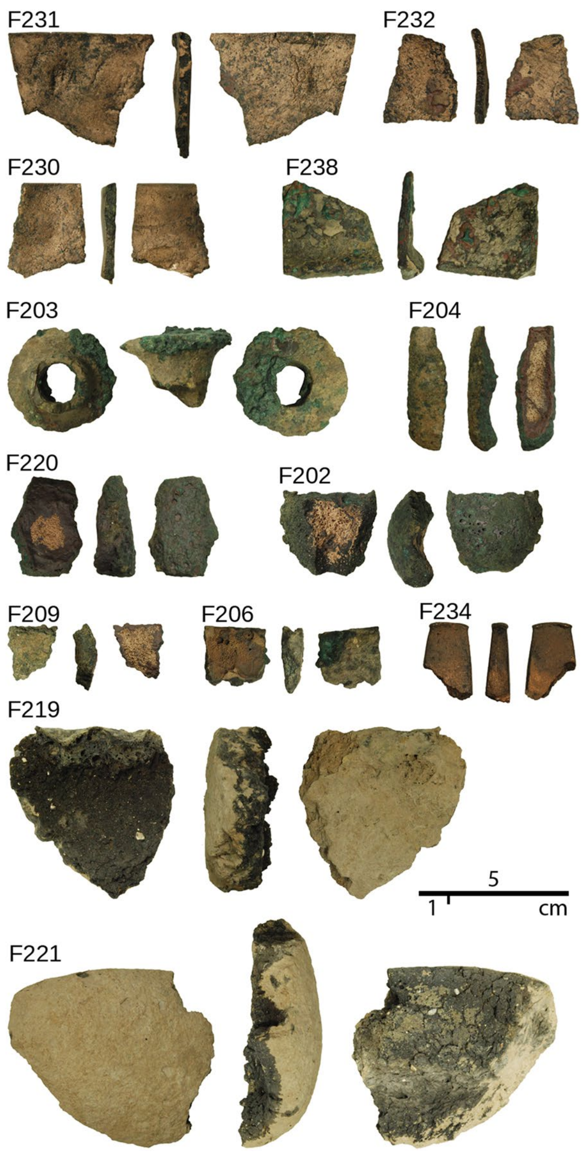

Fig. 2 Selection of metal fragments and two crucible fragments (F219, F221) found in Fazael 2. The labels are the catalogue number given in [18] (rescaled and rearranged photgraphs from Figs. 4–7, 9, 12, 13 in Rosenberg et al. [18], licensed under CC-BY 4.0)

25 kV acceleration voltage in high vacuum mode on the uncoated section.

Infrared spectroscopy was performed by carefully removing 1 g of representative material from each sample and homogenizing the powder in an agate mortar. Approximately 0.2 mg was ground to a fine powder and afterwards mixed with approximately 20 mg of KBr (FTIR-grade). Samples were then pressed into a 7-mm pellet using a hand press (PIKE Technologies). Infrared spectra were obtained using a Thermo Scientific Nicolet iS5 spectrometer at 4 cm^{-1} resolution. Analysis was performed in OMNIC software.

Results

Petrography and SEM-EDX

Crucibles and burnt glazed sediments

Crucibles and burnt glazed sediments can be separated into three petrographic groups. The first group comprises F225 and F229 (Fig. 5). No indication of extensive heating, such as vitrification or slagging, was observed (Table 1). Reddish soft material on the concave side of both sherds could indicate localised strong heating. The cross-section of F225 suggests that it is a base fragment of a bowl-shaped vessel with a flat base (Fig. 3b). The subparallel cracks in the section align with its inner surface (Fig. 4a). The clay in the sections of both items is orange-brown, calcareous, and has abundant rhomboidal carbonate crystals, dolomite, and, less abundant, iron oxide aggregates. It is optically active with domains subparallel to the convex surface in F225-cr. Also, in F225-cr, a few foraminifera were observed in the clay matrix. The sand-sized non-plastic inclusions are predominantly subangular carbonate grains and, in decreasing abundance, chert, larger iron oxide aggregates, and molluscs. Vegetal matter is absent except for a single grass leaf in F229-cr. This paste corresponds very well with clay derived from the Moza formation [15, 29, 30].

F225a is the only member of the second group. Similar to the first group, it is made from orange to brown calcareous clay with iron oxide aggregates. However, rhomboidal carbonate crystals are absent, and foraminifera are considerably more abundant than in the former group (Fig. 6a). It is weakly optically active with some randomly orientated domains. The most abundant non-plastic inclusion is grass, indicated by elongated pores with charred remains in them. Next are sand-sized carbonates and rare molluscs, chert, and quartz grains. The greyish or darker colour of some areas in F225a-cr could indicate heating (Fig. 6b) but based on its overall appearance only to relatively low temperatures.

The last group comprises F219, F222, and F228. This group is clearly different from the other two groups by the black colour of the sherds. F219 and F228 show extensive bloating due to excessive heating. Under the stereomicroscope, small blue minerals and small vitrified patches were found on F219 (Fig. 7a, b). Unfortunately, the vitrified patches could not be analysed because they are on the top of the rim, and the fragment is too large to fit into the sample chambers of the available SEMs. The blue colour of the crystals and the intense green and red colour of the slag might indicate elevated levels of copper and iron. In contrast to the information provided in

Table 1 List of analysed items, their archaeological details, and key results of the analyses. Maximum firing temperature estimates according to Berna et al. [28]. Abbreviations: Ca = calcite; Qtz = quartz; and Cl = clays, N.A. = not available

Object ID	Locus	Basket	Type	Features	Paste (Petrography)	Mineralogical composition (FTIR)	Clays' main peak position (cm^{-1})	Estimated firing T_{max} (°C)
F219	225	440	Crucible fragment	Bloated matrix, vitrified patches on surface	Silt-rich clay completely blackened, vegetal matter	Slagged material, Qtz-like structure	1081	> 900
F222	210	335	Crucible fragment	Cross-section shows red and black zones parallel to inside surface, preferred orientation of vegetal matter	Silt-rich clay, mostly blackened, vegetal matter, round aggregates of same clay with almost no silt	Slagged material, Qtz-like structure	1085	> 900
F225	106	446	Vessel fragment	Cracks subparallel to inside surface	Moza clay, carbonaceous sand	Ca > Cl > Qtz	1047	700–800
F225a	106	446	Baked sediment nodule	No shaped surfaces	Calcareous clay, vegetal matter, carbonaceous sand	Ca > Cl > Qtz	shoulder at 1040	500–600
F228	225	503	Crucible fragment	Bloated matrix, preferred orientation of vegetal matter	Silt-rich clay completely blackened, vegetal matter	N.A.	N.A.	N.A.
F229	225	440	Vessel, undiagnostic wall fragment		Moza clay, carbonaceous sand	N.A.	N.A.	N.A.
F2-Y39	361	665	Baked sediment nodule	Two layers: regular paste and finer-grained paste richer in silt	Ferruginous silt-rich clay	Cl > Ca > Qtz	1035	< 400
F2-Y42	361	665	Baked sediment nodule		Ferruginous silt-rich clay	N.A.	N.A.	N.A.
F2-Y52	361	665	Baked sediment nodule		Ferruginous silt-rich clay	Cl > Ca > Qtz	1035	< 400
F2-Y50	361	665	Baked sediment nodule	Areas with roughly chopped subparallel aligned vegetal matter and areas with sand-sized carbonate grains	Ferruginous silt-rich clay, vegetal matter, calcareous sand	Ca > Cl > Qtz	1035	< 400
F2-Y55	361	665	Baked sediment nodule	Less silt than in other sediment nodules, completely blackened, vitreous inclusions	Silt-containing opaque matrix, round aggregates with almost no silt, vegetal matter, carbonaceous sand, vitreous inclusions	Cl > Ca > Qtz	1035	< 400
F2-Y57	363	669	Baked sediment nodule	Particularly silt-rich matrix	Ferruginous silt-rich clay	N.A.	N.A.	N.A.
F2-Y64	366	674	Baked sediment nodule	Finely chopped vegetal matter	Ferruginous silt-rich clay, vegetal matter	Cl > Ca > Qtz	1035	< 400
F2-YA3	351	650	Baked sediment nodule		Ferruginous silt-rich clay, carbonaceous sand, vegetal matter	Cl > Ca > Qtz	1035	< 400
Unfired control	N.A.	N.A.	Clay			Cl > Ca > Qtz	1035	< 400

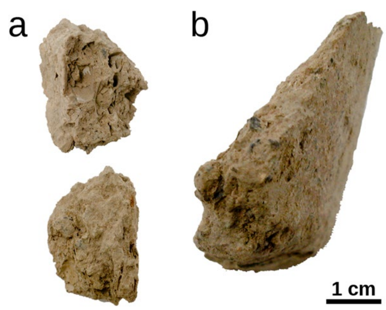

Fig. 3 Selection of samples from Fazael: **a** Sample F225a, the potentially smoothed site is on the left of the upper photo, **b** profile view of F225, highlighting it is a base fragment of a bowl-like vessel with a flat base. See Fig. 12.5 in [18] for additional photos of F225 and Figs. 12 and 13 for photos of the other crucible fragments

Table 4 of Rosenberg et al. [18], no slag could be observed on F222.

The clay is rich (about 50 area%) in silt-sized angular quartz. Iron oxide aggregates and subrounded carbonates are common. The clay is completely opaque black in sections F219-cr and F228-cr (Fig. 7c, d). Unblackened patches in F222-cr indicate a yellowish/orange to brown colour. Additionally, this cross-section reveals a succession of black and red areas in F222 (Fig. 7e). Bloating in F219-cr intensifies towards the rim. A similar gradient of bloating can be observed in F228 as well, but the orientation of this fragment cannot be reconstructed. The paste contains a large proportion of grass, indicated by the shape of the negatives and the regular presence of charred remains in them. The alignment of the plant material in F222-cr indicates a preferred orientation subparallel to the surface of F222. Although not as clear as in F222-cr, the same can be observed in F228-cr. Rare sand-sized carbonate grains were observed in all sections. Additionally, F222 contains distinctive rounded aggregates of up to 1 mm size that can be easily distinguished from the clay matrix by the rare occurrence of silt-sized angular quartz and their consistent black colour, even if the clay matrix around them is not blackened (Fig. 7f).

Baked/heated sediment nodules

All sampled sediment nodules are made of the same clay (Table 1). It is red to dark brown with a large proportion of iron oxides. Between 30 and 50 area% are silt-sized angular minerals, predominantly quartz but also chert, feldspar and heavy minerals, such as amphibole and tourmaline. Carbonates in the size of fine sand are common, molluscs can rarely be found. F2-Y42 and F2-Y52 consist exclusively of this clay; neither mineral nor vegetal non-plastic inclusions were observed (Fig. 8a, b). In section F2-Y39, a layer made of another paste was observed (Fig. 8c). This paste seems to be a finer fraction of the described clay with less iron oxide aggregates and a smaller average grain size. F2-Y50 features in some areas a high proportion of roughly chopped vegetal matter in a subparallel orientation to each other (Fig. 9), while in other areas sand-sized carbonates are abundant. The vegetal matter appears in two "layers" with inclusion-free clay in between. In contrast to this heterogeneous distribution of non-plastic inclusions, the clay itself is homogeneous, and no material contrast is observed. The clay is partially blackened around the vegetal material and has areas where the silt-sized fraction is less abundant or even almost absent. F2-Y57 has a particularly high proportion of the silt-sized fraction (Fig. 8d) and, like F2-Y42

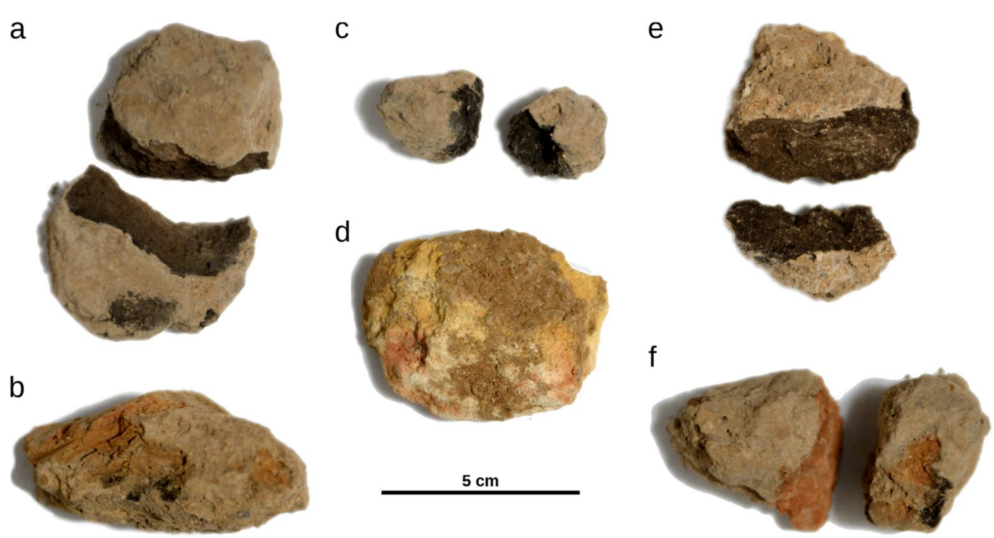

Fig. 4 Selection of sediment nodules from Fazael: **a** F2-Y42, **b** F2-Y50, **c** F2-Y55, **d** F2-Y57, **e** F2-YA3, **f** F2-Y64.

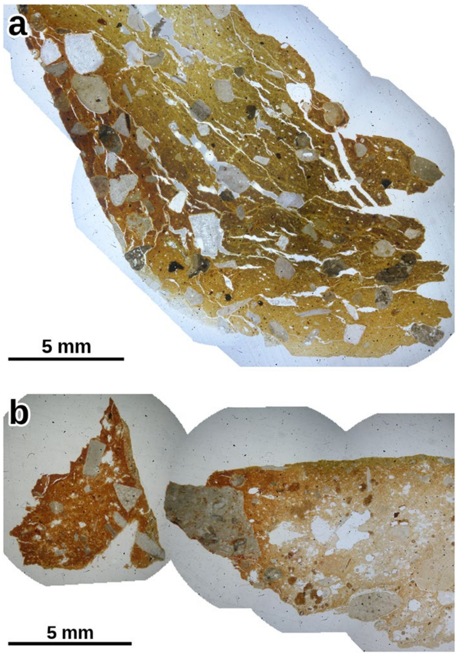

Fig. 5 Photomicrographs of thin sections **a** F225-cr and **b** F229-cr under the stereomicroscope

and F2-Y52, does not contain any non-plastic inclusions. The clay has a dark brown to black colour in this specimen. F2-Y64 features a high proportion of vegetal matter, which is more finely chopped than the vegetal matter in F2-Y50 and randomly orientated (Fig. 8e). F2-YA3 features a high proportion of the silt-sized fraction in the matrix with about equal proportions of vegetal matter and a sand-sized mix of mainly carbonates with chert and shell fragments. Compared to the other sections, it is the richest in non-plastic inclusions (Fig. 8f).

F2-Y55 is distinct from these nodules. It is entirely black to the naked eye. The section shows a black opaque matrix with a less abundant silt-sized fraction than in the other nodules. Similar to F222-cr, rounded areas with less or very little of the silt-sized fraction are present. Non-plastic inclusions are in about equal proportions vegetal matter, carbonates, cherts and shells (Fig. 10a). Additionally, several inclusions up to 0.3 mm diameter are unique to this section. They are orange-brown in plane-polarised light and translucent at crossed polarisers (Fig. 10b), indicating a vitreous material. SEM analyses of three such inclusions revealed a silicate phase with variable concentrations of K, Mg, Ca, Al, and Fe (Table 2). Two analyses are similar in their chemical composition while the third is very rich in Ca and contains significantly less K, Al, Si, and Fe. Most importantly, Cu was not observed. All of them contain a considerable amount of carbon, suggesting that the dark opacified areas in the glass could be carbon (Fig. 10b).

Infrared spectroscopy

Sub-samples of the materials were examined using infrared spectroscopy, a semi-quantitative method for characterizing bulk mineralogical composition. The method allows assessing the maximum temperature clays were exposed to based on changes in the silicates structure [31]. A fragment of the first group (F225), the second group (F225a), and two fragments from the third group (F219, F222) show that the clays' main peak positions differ greatly from the unheated local sediment (Fig. 11a), and that calcite is absent from F219 and is minor in F222. The clays' main peak positions vary greatly, between 1040 and 1085 cm^{-1} (Fig. 11a), indicating a range of maximum temperatures between 600 and 900 °C [28]. However, the nodules show that all the clays' peak positions are around 1035 cm^{-1} (Fig. 11b), which is comparable to the unheated control sediments (Table 1).

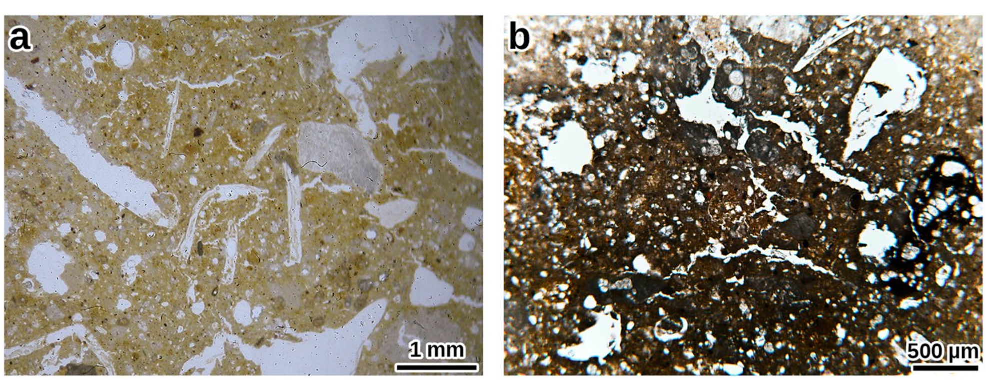

Fig. 6 Photomicrographs of F225a **a** under the stereomicroscope, **b** in plane-polarised light

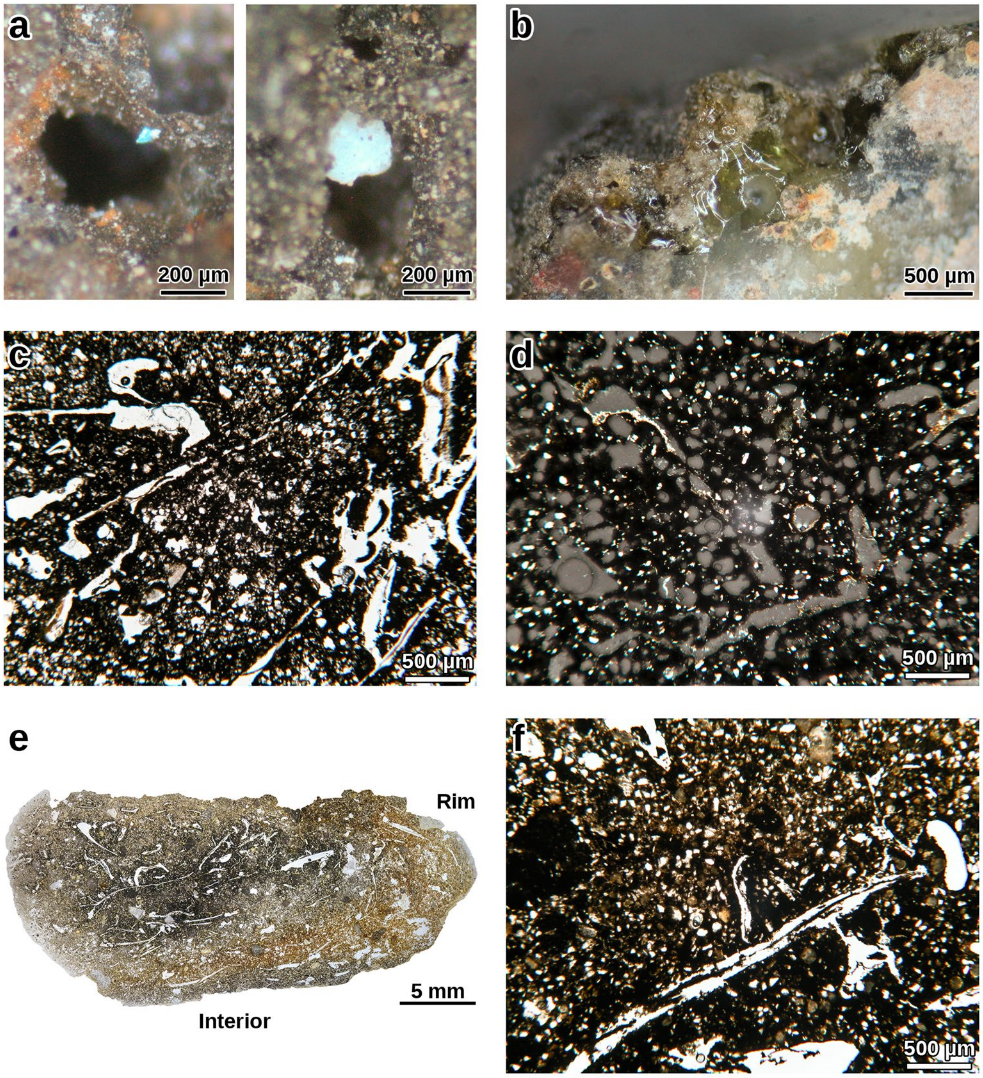

Fig. 7 Photomicrographs of **a** secondary bluish minerals and **b** slag on the rim of F219. Photomicrographs of **c** thin section F219-cr in plane-polarised light and **d** thin section F228-cr in crossed-polarised light. **e** Composite image of the thin section F222-cr showing the different coloured areas of the fragment. **f** Photomicrograph of the same section in plane-polarised light

Discussion

Technology

Rose et al. [32] suggest that ceramics in the Chalcolithic Southern Levant were most likely tempered according to their specific purposes based on the comparison of crucibles fragments, fragments of lost wax casting moulds attached to metal objects, and ceramic vessels. They came to the conclusion that pure chaff temper was exclusively used for metallurgical ceramics, a mix of chaff and mineral temper for lost wax casting moulds and pure mineral temper only for non-metallurgical pottery. Following this differentiation, F225 and F229 are not crucibles, as suggested for F225 [18], but non-metallurgical vessels. The flat base of F225 supports such an interpretation because all known crucibles—including the fragments from Fazael—have rounded bases. In addition, these two sherds do not show traces of excessive heating, such as slagging or bloating.

The exclusive use of chaff temper in all other sampled vessel fragments indicates that they are crucibles. This includes F219, previously interpret as burnt glazed sediment [18]. This interpretation is confirmed by their bloated state and their black colour. Only crucibles and some furnace wall fragments from the Northern Negev sites show comparable features of excessive heating under reducing conditions. The interpretation as crucible fragments is further supported by the presence of slagged areas on the rim of F219 (Fig. 7b) and the

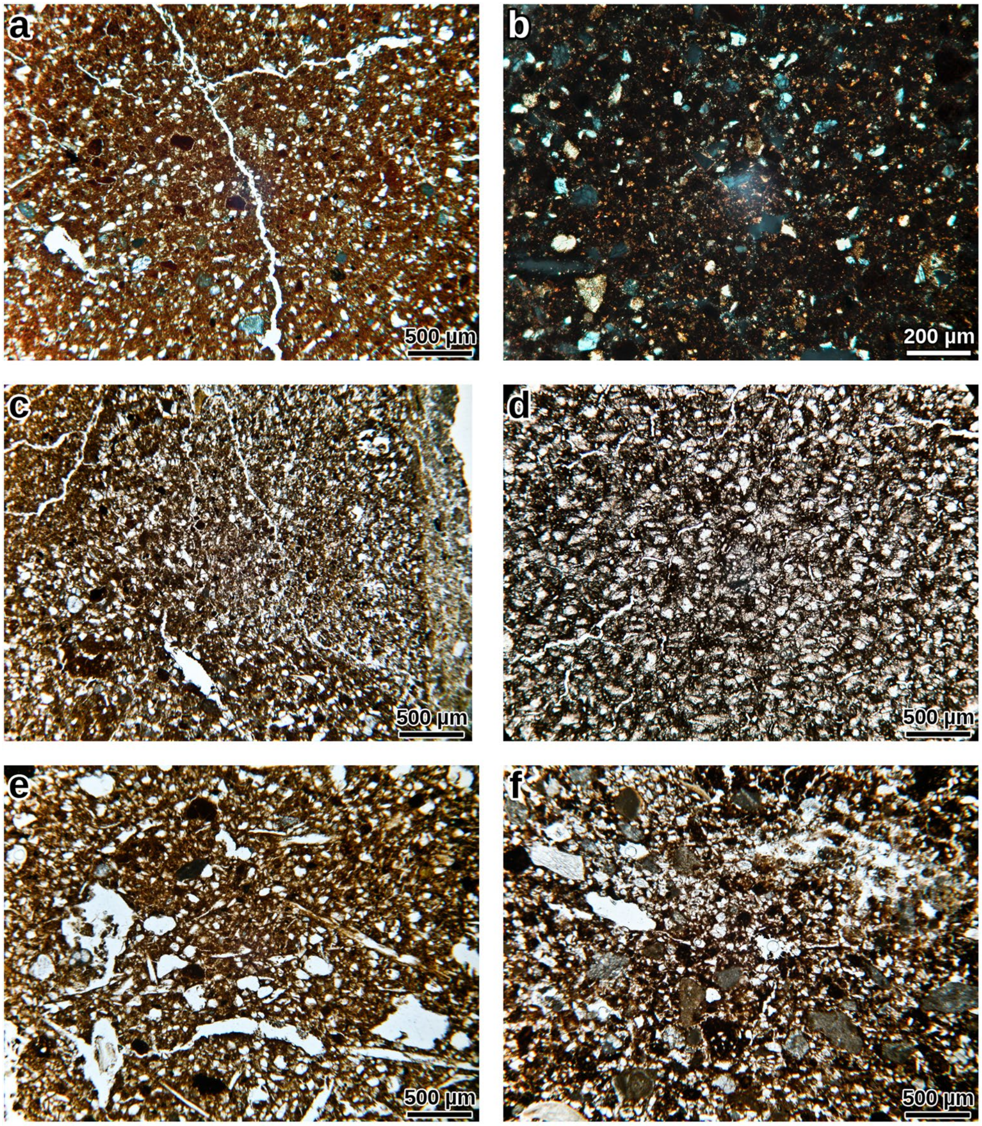

Fig. 8 Photomicrographs of **a** F2-Y52, **b** F2-Y42, **c** F2-Y39, **d** F2-Y57, **e** F2-Y64, **f** F2-YA3; **a**, **c**–**f** in plane-polarised light, **b** in crossed-polarised light. The yellowish layer on the right side of figure **c** is adhering sediment

copper prill on fragment F223 [Table 4 and Fig. 12.3 in 18].

Unfortunately, the sampled fragments are too small to reconstruct the crucible shape. Considering the crucible fragments not available for petrographic examination, a conical shape with a rounded base similar to the crucibles from Abu Matar [8, 33] is likely. The reconstructed diameter is between 8 and 9 cm [Table 4 in 18], considerably smaller than the ~12 cm of the Abu Matar crucibles [33]. The height of several crucibles in Fazael should be smaller as well, considering the substantial curvature of several crucible fragments [18]. The wall thickness and the smoothness of the surface are comparable with some of the crucibles found at the Northern Negev sites. However, the crucible type with a well-smoothed surface that dominates the assemblages of the 1990s excavation in Abu Matar and Horvat Beter seems to be absent [8, 33–36]. Admittedly, this could easily change when more than the present handful of crucible fragments is found in Fazael.

Following the concept of the purpose-specific temper choice [32], some baked sediment nodules may be fragments of lost wax casting moulds. Although the combination of mineral inclusions and vegetal temper was only observed in F2-YA3 (Fig. 8f), both types of non-plastic inclusions are present in F2-Y50 as well, albeit in different

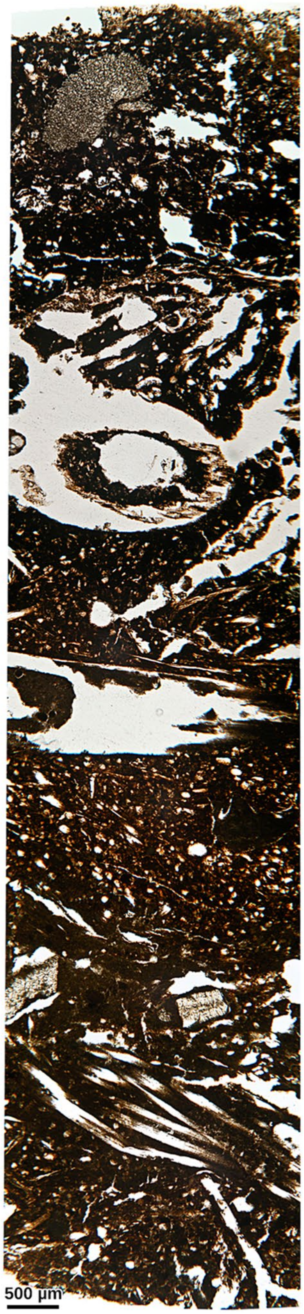

Fig. 9 Photomicrograph of cross section through F2-Y50, plane-polarised light, composite image

parts of the section. The probably strongest argument for the identification of some baked sediment nodules as lost wax casting moulds is the presence of layers, a technological feature exclusive to lost wax casting moulds [15, 16]. Such different layers were observed in F2-Y39 (Fig. 8c), making it likely that this nodule is a mould fragment devoid of non-plastic inclusions (mineral and vegetal). Subparallel orientation of very coarse vegetal material in F2-Y50 with some inclusion-free areas between them might also indicate some kind of layering, albeit without a material contrast (Fig. 9). F2-Y64 could either be a mould or a crucible fragment, as its only notable petrographic feature is the use of vegetal temper. If it is a crucible fragment, it could derive from an unused crucible because the matrix does not show any typical features of the crucible fragments, such as blackening of the clay or charred vegetal material.

The remaining nodules, except F2-Y55, are plain clay without any inclusions or other special features. Their connection to metallurgical ceramics can be inferred because the clay is the same as the other nodules, it has strong similarities to the clay used for the crucibles, and many of them were found at the same spot as the ones discussed previously. Especially the latter renders it very unlikely that they are natural unmodified nodules. It is also unlikely that they are crucible fragments. Crucible fragments have such a high proportion of vegetal matter that the area covered by the sections of the nodules would inevitably have contained some remains of vegetal material. In analogy to the areas void of chaff temper in F2-Y50 and F2-Y39, it seems more likely that they are mould remains or fragments of ceramic cores.

The colour differences in the nodules, e.g., the orange matrix of F2-Y42 and the dark red-brown colour of F2-Y57, F2-YA3 and the finer layer in F2-Y39, might be correlated with the extent of heating the nodules experienced. A change to darker colours with increasing temperature is caused by the heat-induced removal of water in the iron oxyhydroxides and their transformation to haematite. This transformation occurs between 250 and 300 °C [37]. Providing analytical evidence for this hypothesis is very challenging due to the mixture of natural haematite and iron oxyhydroxides in the unfired clay. If this hypothesis holds, the fragments could be related to different parts of Chalcolithic lost wax casting moulds. Given that many of them are part of the same finds cluster, some could even be from the same mould.

F2-Y55 is also part of this cluster. Although its clay paste and non-plastic inclusions correspond to the overall composition of the other nodules, it is markedly different by its blackened matrix and glassy inclusions. Analogous to the crucibles, the blackened matrix indicates most likely heating under reducing conditions and the consequent insufficient combustion of organic compounds such as vegetal matter. However, no charred remains were observed in the negatives of the vegetal matter, different from the crucibles. This apparent contradiction could be explained by the handling of lost wax casting moulds: To remove the wax from the mould, they are heated in an oxidising

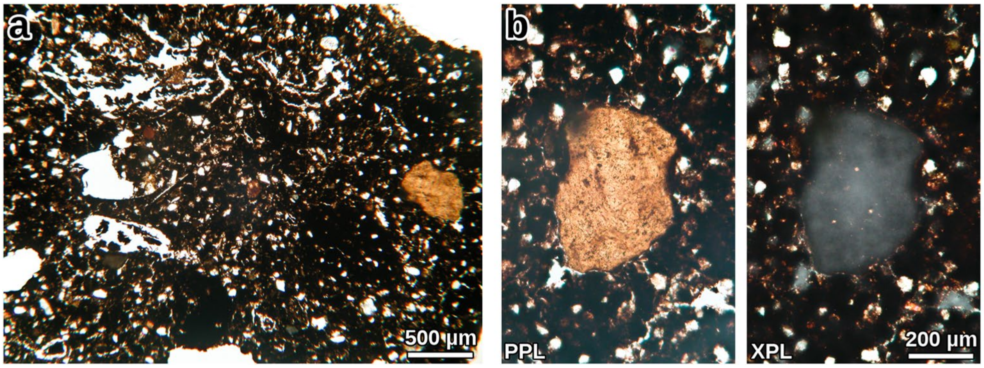

Fig. 10 Photomicrographs of F2-Y55-cr **a** in plane-polarised light, and **b** example of vitreous material in plane (PPL) and crossed-polarised light (XPL).

Table 2 SEM-EDX analyses in wt% for three vitreous inclusions in section F2-Y55.

Point	K	Fe	Mg	Ca	Si	Al	O	C
6_02glass	3.98	14.45	1.92	7.07	27.92	8.93	20.39	15.34
6_04glass	0.54	3.41	2.14	34.84	19.45	2.52	23.83	13.27
6_05glass	5.78	14.29	1.55	7.07	30.03	10.35	22.89	8.05

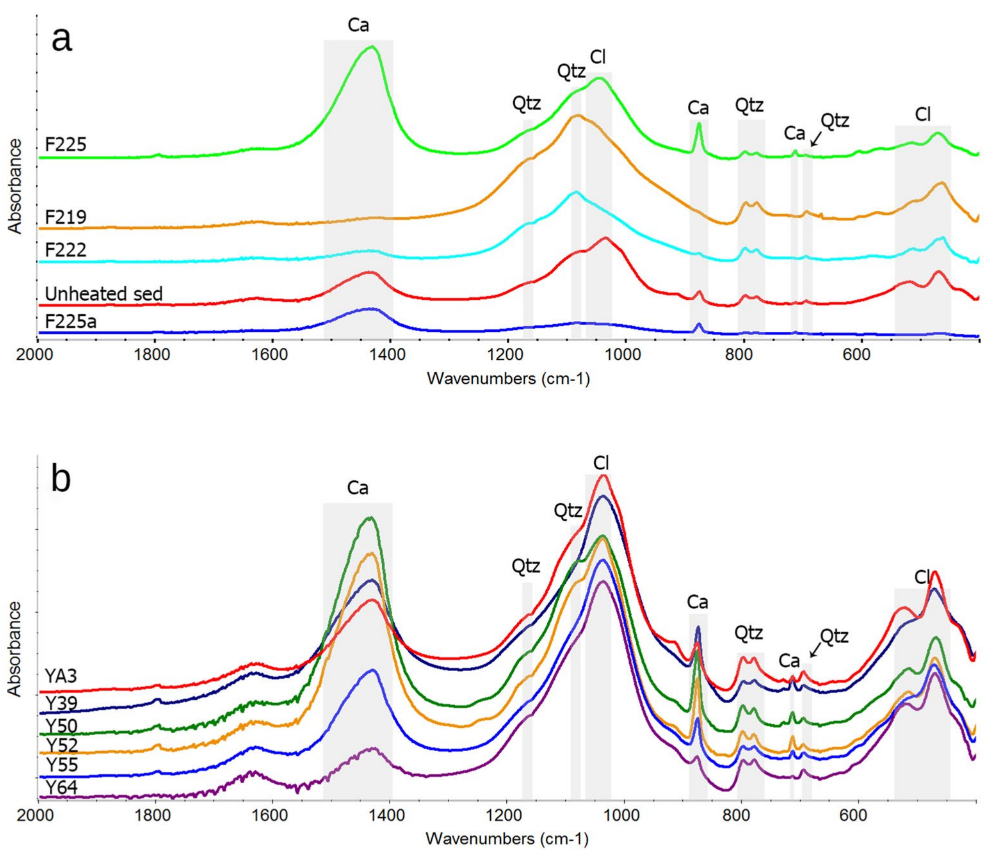

Fig. 11 FTIR spectra of selected samples, indicating the mineralogical composition. Ca: calcite, Qtz: quartz, Cl: clays

atmosphere, creating porosity for the wax and/or the air in the mould by burning the vegetal material. The subsequent casting of the metal will create a reducing atmosphere in the interior of the moulds, which reduces the remaining organic material and blackens the matrix of the mould. Following this line of arguments, F2-Y55 could be a mould fragment very close to the metal melt–mould interface.

The clear borders of the vitreous inclusions to the clay matrix in F2-Y55 indicate that these inclusions were already part of the clay paste and were not created during the firing of the clay. However, their rounded shape shows that they are not crushed material, rendering the addition of crushed slag unlikely. Moreover, the absence of copper in their chemical composition excludes their origin from copper slag. Instead, the inclusions could be remains of vitrified ceramic material without direct contact with melted metal or from pottery production. Anyhow, without additional and ideally larger fragments that contain such vitreous inclusions, their origin cannot be reconstructed.

F225a seems to be a fragment of a baked sediment nodule by its shape, but its clay paste is completely different from the other nodules' clay and the clay used for F225 and F229. Containing vegetal and mineral non-plastic inclusions, it would be placed into the lost wax casting mould category according to the concept of purpose-specific temper choice [32]. At the same time, it is the only nodule with some kind of smoothed surface. A definite interpretation of this nodule is impossible due to its unique nature.

The interpretation of the baked sediment nodules as fragments of lost wax casting moulds is strengthened by the results of the infrared spectroscopy. The baked nodules contain clays that are comparable to the local unheated sediments (see below), and, therefore, were not exposed to temperatures above 400 °C for a long period of time. This is in contrast to the slagged materials, which contain altered clays that were exposed to temperatures above 800 °C (Table 1). In the lost wax technique, the moulds are exposed to high temperatures only when the metal is poured into the mould. This is in accordance with previous research, which suggested that the moulds were not or only moderately preheated before casting [15] and fits perfectly with the very low melting temperature of polymetallic copper alloys of down to 600 °C [38, 39]. Even when vegetal remains were observed in petrographic sections (F2-Y50, F2-YA3), the clays were not exposed to high temperatures. This supports the notion that the metal was for too short a time in the moulds sufficiently hot enough to influence greatly the vitrification of the clays, as is seen in the crucibles.

Provenance of the clay

In addition to the technological interpretation of the ceramic finds, the reconstruction of the clays' provenance is equally important. Goren [15] showed that the clay for the lost wax casting moulds must not necessarily be local because it was purposefully chosen for its refractory properties and was well prepared. Consequently, suitable clay could have been imported to the lost wax casting workshops.

It was already shown that the vessel fragments F225 and F229 are made of clay from the Moza formation. This clay, widely used for domestic pottery and lost wax casting moulds in the Chalcolithic Southern Levant, crops out along the foot of the Judean Plateau [15, 29, 30]. The features of F225a suggest an origin from Rendzina soils. Like the Moza clay, they are available close to Fazael [40, 41].

The clay used for the crucibles and all other nodules is similar to the Negev loess in its amount of silt-sized inclusions of quartz and other minerals but clearly differs in its ferruginous character. Ferruginous loess of similar composition can be found at the banks of the Wadi Fazael close to the site. It has good refractory properties [42]. For an archaeological experiment, the clay was elutriated to separate it from the carbonate sand of the river banks [42]. The so-prepared clay shows all the features observed in the crucible fragments and nodules: A high proportion of silt-sized angular quartz and other minerals, high content of iron-rich material, and a very low proportion of non-plastic inclusions (Fig. 12). The clay of the nodules and crucible fragments has a higher proportion of the silt-sized fraction and iron-rich aggregates than the clay prepared in the experiment. In addition, its content of non-plastic inclusions is lower. However, a clay paste with these properties could be easily prepared

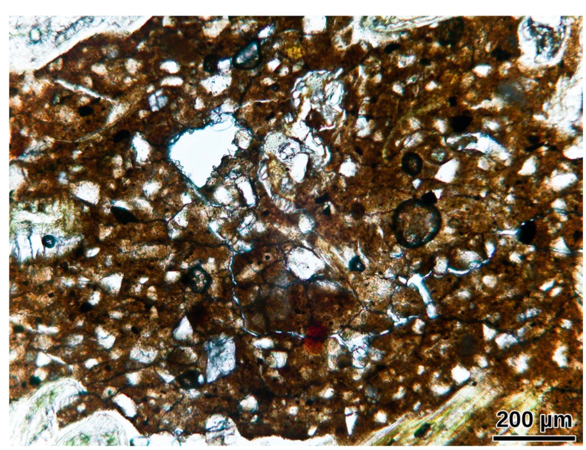

Fig. 12 Photomicrograph of unfired Fazael clay mixed with vegetal matter

from the ferruginous loess in Fazael by applying a preparation protocol that removes the carbonate sand more efficiently and removes part of the clay fraction. Therefore, the clay for the metallurgical ceramics seems to be extracted directly at the site.

Fazael as production site

The Fazael assemblage provides important insight into the processing of polymetallic copper alloys. The slag patches on F219 (Fig. 7b) link the crucibles to copper metallurgy in general, as does the vitrification and bloating of F219 and F228 but not necessarily the processing of polymetallic copper alloys. There is currently only one item that seems to provide direct evidence for such activities: F236, a casting prill made of As-Ni copper [43]. The large number of fragments from lost wax cast items might be seen as tentative evidence for the production of such items in Fazael 2, too. However, being scattered all over the site with no apparent pattern [18], they might be the result of the (deliberate) destruction of such objects rather than fragments collected for e.g., recycling.

The findings of this study provide strong evidence for the identification of Fazael 2 as first ever found lost wax casting site of the Chalcolithic Southern Levant. Admittedly, this resulted from the overall view of the presented evidence rather than a "smoking gun". Some of the heated sediment nodules show features that must be considered specifically for lost wax casting moulds, such as multiple layers and the combination of chaff and mineral temper. While this holds true only for some of the analysed nodules, the fact that the other nodules were found with them and have the same overall appearance strongly suggests that they are fragments of lost wax casting moulds, too.

A location of the polymetallic copper alloy processing site(s) in the Jordan Valley would fit with the observation that the Jordan Valley is more closely related to regions further north, from where the polymetallic copper alloys were derived than it is to other regions in the Chalcolithic Southern Levant [44–47]. It must remain speculative whether the beneficial physical or potential symbolic properties of the ferruginous loess at Fazael were of importance for the location of the lost wax casting workshop(s). In any case, the Fazael area was already populated before the broad room house in Fazael 2 was built, and settlement activities in the area continued after the end of the Chalcolithic [19, 48]. Thus, it should be expected that knowledge about the properties of the local clay was already available before the onset of the metallurgical activities in Fazael.

The location of a lost wax casting workshop at Fazael has important implications for our understanding of the Chalcolithic Southern Levantine metallurgy. Most important, metallurgical operations were apparently not restricted to the Northern Negev as the archaeological record suggested so far [49] but were also carried out in the Jordan Valley. The admittedly scarce evidence further suggests that these activities might have been exclusively related to the processing of polymetallic copper alloys. This could imply a spatial separation of the unalloyed copper technology in the Northern Negev and the polymetallic copper alloys in the Jordan Valley. Further, the findings confirm the results of Goren [15], who localised the production site(s) of the lost wax cast objects somewhere in the Jordan Valley based on the occurrence of the different clays used in the mould remains he investigated. However, ferruginous loess is not among the clay pastes previously described as mould material for Chalcolithic Southern Levantine lost wax cast objects [15]. Consequently, more than one production site for lost wax casting must be assumed.

Conclusions

Excavations in Fazael yielded a large number of metal objects, most of them fragments of polymetallic copper alloys and several crucible fragments. While the archaeological context of the metal items and the crucible fragments was already previously presented [18], its technological aspects remained so far unstudied. In addition, heated sediment nodules were found in a later excavation season and identified as potential remains of lost wax casting moulds. A selection of crucible fragments and heated sediment nodules were investigated by petrography, SEM-EDX, and FTIR analysis to gain new insights into the metallurgical practices and to investigate if Fazael can securely be identified as a lost wax casting site.

The results of the analyses confirmed the presence of crucibles for copper metallurgy at the site. Furthermore, several of the heated sediment nodules have features that are characteristic of lost wax casting moulds and the remaining ones were found together with them and share the same general features. Crucibles and nodules are made of the same ferruginous loess, which is available on the riverbanks of the Wadi Fazael. Based on this evidence, Fazael can be interpreted as the first identified lost wax casting site of the Chalcolithic Southern Levant. At the same time, the ferruginous loess was not described as mould material in previous studies [15, 16], indicating the presence of more than one lost wax casting workshop in the Chalcolithic Southern Levant. With these results at hand, it is obvious that metallurgy in the Chalcolithic Southern Levant is not restricted to the confines of the Northern Negev.

Because the available material is very limited, further studies would allow providing important additional information. Studying more of the nodules would help to substantiate the conclusions drawn from this subset. Moreover, excavations are still ongoing. They might provide material with hitherto uncovered features, and allow further refinement of our understanding of the polymetallic copper alloy metallurgy, the lost wax casting process and the organisation of the production site.

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Author contributions
TR: Conceptualization, formal analysis, investigation, visualisation, writing—original draft, writing—review and editing; SB: Resources, writing—review and editing. YA: Investigation, visualisation, writing—original draft, writing—review and editing; YG: Conceptualization, investigation, funding acquisition, project administration, supervision, writing—review and editing.

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Availability of data and materials
All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
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Competing interests
The authors declare no competing interests.

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References

1. Leusch V, Armbruster BR, Pernicka E, Slavčev V. On the invention of gold metallurgy: the gold objects from the Varna I Cemetery (Bulgaria)—technological consequence and inventive creativity. Camb Archaeol J. 2015;25:353–76.
2. Higham T, Slavchev V, Gaydarska B, Chapman J. AMS dating of the late copper age Varna Cemetery, Bulgaria. Radiocarbon. 2018;60:493–516.
3. Thoury M, Mille B, Séverin-Fabiani T, Robbiola L, Réfrégiers M, Jarrige J-F, et al. High spatial dynamics-photoluminescence imaging reveals the metallurgy of the earliest lost-wax cast object. Nat Commun. 2016;7:1–8.
4. Roux V. Technological innovations and developmental trajectories: social factors as evolutionary forces. In: O'Brien MJ, Shennan SJ, editors. Innovation in cultural systems. Cambridge; London: MIT Press; 2010. pp. 217–33.
5. Dardeniz G. Why did the use of antimony-bearing alloys in bronze age Anatolia fall dormant after the early bronze age? A case from Resuloğlu (Çorum, Turkey). PLoS ONE. 2020;15:e0234563.
6. Bar-Adon P. The Cave of the treasure. Jerusalem: The Israel Exploration Society; 1980.
7. Golden JM, Levy TE, Hauptmann A. Recent discoveries concerning Chalcolithic metallurgy at Shiqmim, Israel. J Archaeol Sci. 2001;28:951–63.
8. Golden JM. Dawn of the metal age: Technology and society during the Levantine Chalcolithic. New York: Routledge; 2014.
9. Hauptmann A. The earliest periods of copper metallurgy in Feinan, Jordan. In: Hauptmann A, editor. Old world Archaeometallurgy. Bochum: Deutsches Bergbau-Museum Bochum; 1989. pp. 119–35.
10. Hauptmann A. The archaeometallurgy of copper: evidence from Faynan, Jordan. Berlin: Springer; 2007.
11. Shalev S, Northover JP. Chalcolithic Metal and Metalworking from Shiqmim. In: Levy TE, editor. Shiqmim 1. Oxford; 1987. p. 357–73.
12. Shugar AN. Reconstructing the Chalcolithic Metallurgical Process at Abu Matar, Israel. In: Associazione Italiana di Metallurgia, editor. Archaeometallurgy in Europe. Milano; 2003. p. 449–58.
13. Shugar AN. Extractive metallurgy in the Chalcolithic Southern Levant: assessment of copper ores from Abu Matar. In: Ben-Yosef E, editor. Mining for ancient copper. Winona Lake, Indiana: Eisenbrauns; 2018. pp. 276–96.
14. Tadmor M, Kedem D, Begemann F, Hauptmann A, Pernicka E, Schmitt-Strecker S. The Naḥal Mishmar Hoard from the Judean Desert: technology, composition, and provenance. 'Atiqot. 1995;27:95–148.
15. Goren Y. The location of specialized copper production by the lost wax technique in the Chalcolithic southern Levant. Geoarchaeology. 2008;23:374–97.
16. Goren Y, Gods. Caves, and Scholars: Chalcolithic cult and metallurgy in the Judean Desert. Near East Archaeol. 2014;77:260–6.
17. Shalev S, Goren Y, Levy TE, Northover JP. A Chalcolithic mace head from the Negev, technological aspects and cultural implications. Archaeometry. 1992;34:63–71.
18. Rosenberg D, Buchman E, Shalev S, Bar S. A large copper artefacts assemblage of Fazael, Jordan Valley: new evidence of Late Chalcolithic copper metallurgy in the Southern Levant. Doc Praehistorica. 2020;47:246–61.
19. Bar S, Bar-Oz G, Cohen-Klonymus H, Pinsky S. Fazael 1, a Chalcolithic site in the Jordan Valley: report of the 2013–2014 Excavation Season. J Israel Prehist Soc. 2014;44:180–201.
20. Bar S, Bar-Oz G, Ben-Yosef D, Boaretto E, Raban-Gerstel N, Winter H. Fazael 2, one of the latest Chalcolithic sites in the Jordan Valley? Report of the 2007–2008 excavation seasons. J Israel Prehist Soc. 2013;43:148–85.
21. Bar S, Cohen-Klonymus H, Pinsky S, Bar-Oz G, Shalvi G. Fazael 5: soundings in a Chalcolithic site in the Jordan Valley. J Israel Prehist Soc. 2015;45:193–216.
22. Bar S, Cohen-Klonymus H, Pinsky S, Bar-Oz G, Zuckerman R, Shalvi G, et al. Fazael 7: a large Chalcolithic architectural complex in the Jordan Valley, the 2009–2016 excavations. J Israel Prehist Soc. 2017;47:208–47.
23. Porath Y. A chalcolithic building at Fasa'el. 'Atiqot. 1985;17:1–19.
24. Eshed V, Bar S. An innovative analysis of infant burials from the Chalcolithic Site of Fazael 2, Israel. Isr Explor J [Internet]. 2012;62:129–40. Available from: www.jstor.org/stable/43855620.
25. Gilead I. Chalcolithic Culture History: Ghassulian and other entities in the Southern Levant. In: Lovell JL, Rowan YM, editors. Culture, chronology and the Chalcolithic. Oxford: Oxbow Books; 2011. pp. 12–24.
26. Bar S, Winter H. Canaanean flint blades in Chalcolithic context and the possible onset of the transition to the Early Bronze Age: a case study from Fazael 2. Tel Aviv. 2010;37:33–47.
27. Cohen-Klonymus H, Bar S. Ground stone tool assemblages at the end of the Chalcolithic period: a preliminary analysis of the Late Chalcolithic sites in the Fazael Valley. J Lithic Stud. 2016;3:103–23.
28. Berna F, Behar A, Shahack-Gross R, Berg J, Boaretto E, Gilboa A, et al. Sediments exposed to high temperatures: reconstructing pyrotechnological processes in Late Bronze and Iron Age Strata at Tel Dor (Israel). J Archaeol Sci. 2007;34:358–73.
29. Goren Y. Shrines and Ceramics in Chalcolithic Israel: the view through the Petrographic Microscope. Archaeometry. 1995;37:287–305.
30. Goren Y. The technology of the Gilat pottery assemblage: a reassessment. In: Levy TE, editor. Archaeology, anthropology and cult. London: Equinox; 2006. pp. 369–95.
31. Weiner S. Microarchaeology: beyond the visible archaeological record. Cambridge: Cambridge University Press; 2010.

32. Rose T, Fabian P, Goren Y. The (in)visibility of lost wax casting moulds in the archaeological record: observations from an archaeological experiment. Archaeol Anthropol Sci. 2023;15:31.
33. Shugar AN. Archaeometallurgical Investigation of the Chalcolithic Site of Abu Matar, Israel: A Re-assessment of Technology and its Implications for the Ghassulian Culture [PhD thesis]. [London]: University of London; Institute of Archaeology; 2000.
34. Ackerfeld D, Abadi-Reiss Y, Yagel O, Harlavan Y, Abulafia T, Yegorov D, et al. Firing up the furnace: new insights on metallurgical practices in the Chalcolithic Southern Levant from a recently discovered copper-smelting workshop at Horvat Beter (Israel). J Archaeol Science: Rep. 2020;33:102578.
35. Hauptmann A, Lutz J, Pernicka E, Yalçin Ü. Zur Technologie der frühesten Kupferverhüttung im östlichen Mittelmeerraum [About the earliest copper smelting technology in the Eastern Mediterranean] (in German). In: Frangipane M, Hauptmann H, Liverani M, Matthiae P, Mellink M, editors. Between the Rivers and over the mountains. Dipartimento di Scienze Storiche Archeologiche e Anthropologiche dell'Antichità. Università di Roma "La Sapienza"; 1993. pp. 541–72.
36. Perrot J. The excavations at tell Abu Matar, near Beersheba. Isr Explor J. 1955;5:73–84.
37. Palacios PR, Bustamante A, Romero-Gómez P, González JC. Kinetic study of the thermal transformation of limonite to hematite by X-ray diffraction, μ-Raman and Mössbauer spectroscopy. Hyperfine Interact. 2011;203:113–8.
38. Massalski TB, editor. Binary Alloy Phase Diagrams. 2nd ed. Materials Park, Ohio: ASM International; 1986.
39. Northover JP. Analysis of copper alloy metalwork from Arbedo TI. In: Schindler MP, editor. Der Depotfund von Arbedo TI und die Bronzedepotfunde des Alpenraums vom 6 bis zum Beginn des 4 Jh v chr. Basel: Verlag Schweizerische Gesellschaft für Ur- und Frühgeschichte; 1998. pp. 289–315.
40. Ravikovitch S. Soil map: Israel North. Tel Aviv: Survey of Israel; 1969.
41. Dan Y, Raz Z, Yaalon H, Koyumdijsky H. Soil Map of Israel [Internet]. Tel Aviv: Survey of Israel; 1975. Available from: https://esdac.jrc.ec.europa.eu/content/soil-map-isra%C3%ABl.
42. Rose T, Fabian P, Goren Y. Shedding new light on the pure copper metallurgy of the Chalcolithic Southern Levant through an archaeological experiment. EXARC Journal. 2021;2021:1–11.
43. Rose T, Natali S, Brotzu A, Bar S, Goren Y. First evidence for alloying practices in the Chalcolithic Southern Levant (4500–3800 BCE) as revealed by metallography. Heritage Sci. 2023. https://doi.org/10.1186/s40494-023-01030-2.
44. Gabrieli E. Contacts between the Southern and Northern Levant in the first half of the 5th millennium BC: a pottery perspective from Jordan. Paléorient. 2016;42:151–84.
45. Rosenberg D, Shimelmitz R. Perforated stars: networks of prestige item exchange and the role of perforated flint objects in the Late Chalcolithic of the Southern Levant. Curr Anthropol. 2017;58:295–306.
46. Rosenberg D, Groman-Yaroslavski I, Chasan R, Shimelmitz R. Additional thoughts on the production of Chalcolithic perforated flint tools: a test case from Tel Turmus, Hula Valley, Israel. In: Astruc L, McCartney C, Briois F, Kassianidou V, editors. Near Eastern lithic technologies on the move: 8th International Conference on PPN Chipped and Ground Stone Industries of the Near East, Nicosia, November 23rd-27th 2016. Nicosia: Astrom Editions; 2019. p. 415–26.
47. Streit K, Garfinkel Y. Tel Tsaf and the impact of the Ubaid Culture on the Southern Levant: interpreting the Radiocarbon evidence. Radiocarbon. 2015;57:865–80.
48. Zutovski K, Bar S. Canaanean Blade Knapping Waste Pit from Fazael 4, Israel. Lithic Technol. 2017;42:109–25.
49. Golden JM. Who Dunnit? New clues concerning the development of Chalcolithic Metal Technology in the Southern Levant. In: Roberts BW, Thornton CP, editors. Archaeometallurgy in global perspective. New York, NY: Springer; 2014. pp. 559–78.

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