



Hidden riches in the Early Medieval Rhine Delta: Iron working at Merovingian Oegstgeest

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ABSTRACT

Long dismissed as a backwater, increased study of the Rhine Delta in the Early Middle Ages has revealed considerable wealth and prosperity in even the most isolated of sites. The 6th–8th century Merovingian settlement at Oegstgeest is a good example of such. Despite its seeming remoteness and small size, its excavation found evidence for the creation and importation of quality goods, seemingly without any connection to existing elite structures. This study examined one aspect of this prosperity (iron working) to gain a better understanding of the role of Oegstgeest within its socioeconomic environment. Metallurgical and chemical characterisation was undertaken on thirteen metal samples and twenty-three slag samples from Oegstgeest. The results of this study established the use of quality metals and advanced forging techniques. This suggests that the inhabitants of Oegstgeest had the required contacts to obtain such materials, as well as the presence of skilled artisans with the time and demand to put their experience into practice. Further study found definite evidence of iron and copper alloys being worked in tandem. A provenance study was also undertaken on the metallic samples. Possible matches were established between the material from Oegstgeest with Lorraine in Eastern France as well as a potential connection to Southern Germany. In short, the results of this study suggest complement that of other the other finds of the settlement, suggesting that Oegstgeest was integrated into regional trade networks of the Early Middle Ages.

1. Introduction

The Early Medieval Rhine Delta has traditionally been viewed as a literal and metaphorical backwater. Prone to constant flooding, far removed from the halls of power that long hoarded the attention of the literature (Pirenne 1937; Besteman et al., 1990), the region has often been considered isolated and poor. The confusion surrounding the departure of the Western Roman Empire, leading to major changes in ethnic and cultural make-up (Wood 1994; van Es & Verwers 2010) has contributed to this perception. In conjunction with the depopulation of urban centres and the lack of written records, these factors have led to the period being one of the poorest understood in the history of the Netherlands. However, the study of rural settlements over the past four decades has challenged these prevailing assumptions. Many such settlements are decidedly prosperous and show evidence for medium to

long distance trade, all while existing outside the traditional framework of secular and religious elites (Loveluck & Tys 2006; Henning 2007). In spite of this, many aspects of this period remain unclear. For instance, whilst its existence has been known for some time, iron working in rural settlements remains poorly understood.

The Merovingian settlement at Oegstgeest is a good example of this. Despite its small size and apparent isolation from existing power structures, the excavations at this site found clear evidence of trade and local production of a variety of materials, including ironworking. Prior to this study, the iron slag, metallic forge scrap and finished objects from this site have only undergone preliminary macroscopic analysis. By studying this material in depth, this paper intends to establish the realities of ironworking at Oegstgeest, considering the techniques and materials available to the inhabitants of the site. In time, the hope is that these results will contribute to the growing body of study into the socio-

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economic role of such rural settlements in the Early Medieval Rhine Delta.

1.1. Archaeological context

1.1.1. Merovingian Oegstgeest

The Merovingian settlement at Oegstgeest is located in South Holland near the mouth of the Oude Rijn, 2 km west of Leiden and 3 km south of the modern town of Oegstgeest. The site underwent a series of excavations, led primarily by Leiden University, between 2004 and 2018. These campaigns uncovered much of the site, making it one of the best excavated Early Medieval settlements in the Western Netherlands (Kars et al., 2018).

Buildings at Oegstgeest were split into a series of yards of one to two houses each, distributed across the settlement in five clusters (see Fig. 1, clusters marked A–E). The waterlogged conditions at Oegstgeest were ideal for wood preservation, allowing for widespread dendrochronological study (Theuvs et al., 2021a). The earliest attributed date is 555 CE, which matches the pottery recovered from the settlement though some sherds suggest that the first occupation may have been slightly earlier. A lack of dates from the early 7th century was interpreted by Theuvs et al. (2021a) as evidence that Oegstgeest was briefly abandoned due to widespread flooding in the Rhine Delta at this time. The settlement was re-occupied by 650 CE and the latter half of the 7th century seems to have been the heyday of the site, with the majority of datable finds and buildings being from this period. The last reliable dendrochronological date is 700 CE (de Bruin 2021; Theuvs et al., 2021a) though the presence of *sceattas* (silver coins) dating to later periods suggest that the settlement may not have been fully abandoned until c. 725–730 CE. The precise reason for the abandonment of the settlement is unclear though Theuvs et al. (2021a) theorise that it could be related to a migration of the Rhine River around this time.

The landscape around Oegstgeest was regularly in flux and the settlement itself was built on a series of gullies connecting to the main river. Flooding would have been a perennial risk, which combined with the lack of trees in the area, encouraged heavy reuse of wood. This contributed to the difficulties experienced by Theuvs et al. (2021a) in establishing a precise end date for the settlement. Between this reuse and the relatively short occupation (175 years at most), establishing clear phases of occupation was not possible. However, Theuvs et al. (2021a) suggest that while there may have been buildings in each cluster at any given time, the main centre of the settlement appears to have shifted during the occupation. They believe that cluster B is the oldest section of the settlement, due to its association with the earliest dendrochronological dates, with cluster D possibly being occupied last. Due to this uncertainty, giving a population estimate for the settlement is difficult. Nevertheless, Theuvs et al. (2021a) posit that there may have been 60 people living at Oegstgeest at any moment of its existence.

Despite the settlement's proximity to the coast, Oegstgeest was primarily a riverine site. At the time, the Oude Rijn was one of the largest tributaries of the Rhine Delta and this had a major effect on the character of the settlement. Oegstgeest appears to have been a logical stopping point between the North Sea and the lands upriver (Theuvs et al., 2021a), a connection reinforced by the large number of imports identified during excavation. These include simple finds, such as wooden bowls and everyday utensils but also more complex objects. For example, 122 glass shards were recovered from the settlement, the majority of which came from vessels or other containers (Van Wersch 2021). These were typologically consistent with vessels dating to the 6th and 7th centuries, suggesting that glass was imported during the entire occupation of the site. Other finds included glass beads; some produced locally, some from as far as the Mediterranean, worked amber from the Baltic, as well as several exceptional finds, including a silver bowl from the Mediterranean. Theuvs et al. (2021a) also found evidence of imported foodstuffs. Several wooden barrels were found to have contained wine, likely from the middle Rhine and further study confirmed the

presence of grain, rye, grapes, figs and possibly walnuts, none of which are likely to have grown in the region. Evidence of cross North Sea trade was also present, visible through 24 silver *sceattas*, mostly of the D and E series, a type found in both England and the Netherlands. In addition, an English style horse bit was uncovered, though it is unclear whether this was imported from England or made locally in English style.

There was also clear evidence of local production. Three soled leather shoes, a rarity at this period, were found at Oegstgeest alongside the materials and tools required to make them (Theuvs et al., 2021a). Additional evidence for local production included metalworking: other than the remains of iron working covered by this paper, 3 gold ornaments and over 200 finds related to copper working were uncovered. Most of these were brooches though several crucible fragments were also found, one of which was attached to a copper alloy fragment. These metal finds were fragmented and seem to have been in the process of being recycled (Theuvs et al., 2021b).

1.1.2. Iron in the Early Medieval Netherlands

The material from Oegstgeest has already undergone initial macroscopic study (Disser 2019; Theuvs et al., 2021b) which, in combination with the study of the wider site (de Bruin et al., 2021) found no evidence for primary iron production at Oegstgeest. This suggests that the iron worked on site came from elsewhere, making an understanding of iron production and iron working in the Early Medieval Netherlands crucial to fully understand the settlement within its wider context.

The Netherlands is not known for its mineral resources but there is clear evidence of iron production in the region in the Early Medieval period (Joosten 2004). Many Dutch smelting sites relied on bog iron ore, accumulations of iron rich minerals precipitated in sandy, silty or clayey sediments (Thelemann et al., 2016), but there is also evidence for the use of other kinds of mineral deposits. This is especially true in the Central and Eastern Netherlands with the most prominent Early Medieval example being the Veluwe (Gelderland). Wide-spread iron smelting in this area became a phenomenon as early as the 7th century and this continued until the mid-9th century (Joosten 2004). More than 70 slag heaps have been identified in the region, as well as numerous open cast mining pits and deposits of rattle stone ore in certain strata. Alongside these local sources, given the presence of imported objects at Oegstgeest and other similar sites, it is likely that smiths in the Early Medieval Netherlands were using iron from further afield.

In contrast, there has been little study of smithing activities in this region. The few extant papers focus on the typology of individual finds rather than wider questions of production. Furthermore, centres of trade and power such as Dorestad and Nijmegen typically take centre stage with rural contexts being ignored (c.f. Ellis 2002; Willemsen et al., 2021). Worked iron has been identified and characterised at some smelting sites; such as Heeten in Overijssel (Godfrey & van Nie 2004) but these again focus on individual finds. Joosten (2004) also documented some possible smithing slags from the Veluwe but these were not characterised further. It is for this reason that the study of a rural site like Oegstgeest is of such interest, as it offers a window into two understudied contexts.

1.2. Iron working at Oegstgeest

Over 43 kg of iron slag was recovered from Oegstgeest alongside 2.4 kg of metallic finds (see Fig. 2a). As of yet, no forge or metal workshop has been identified at Oegstgeest and the distribution of the remains of iron working at the settlement has unfortunately not aided in the identification of any such structure. However, the ironworking finds from Oegstgeest do fit within the four main clusters identified by Theuvs et al. (2021a) (A–D, see Fig. 3). Forge slag appears to be concentrated in specific areas, notably in clusters C and D but all four clusters contained some hearth bottoms. Furthermore, these appear to be disassociated from the forge scrap, the other primary indicator of forge activities, as these were found in clusters A and B. As most of the hearth

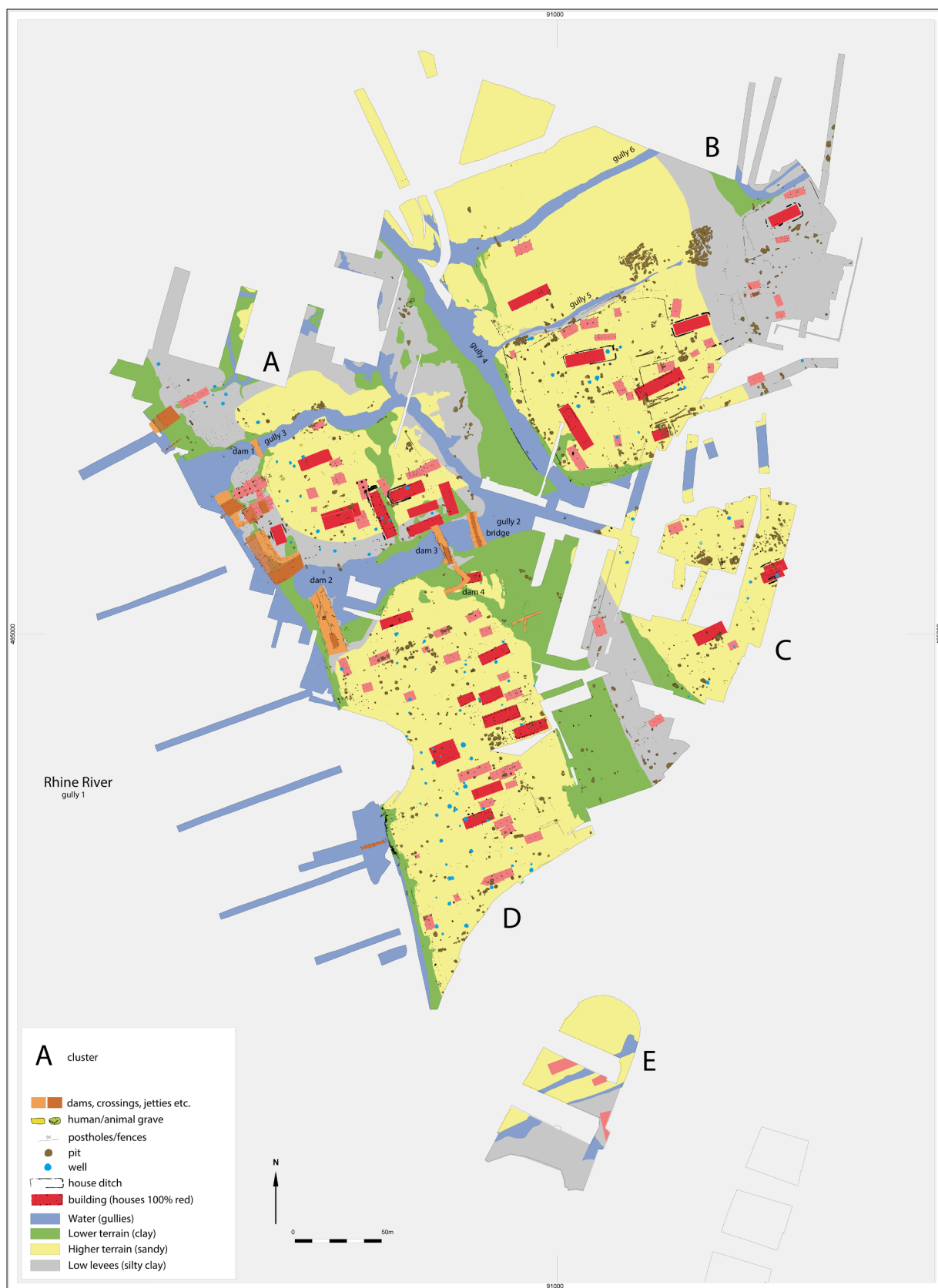


Fig. 1. Map of the Merovingian settlement at Oegstgeest.
adapted from [Theuvs et al., 2021a](#)

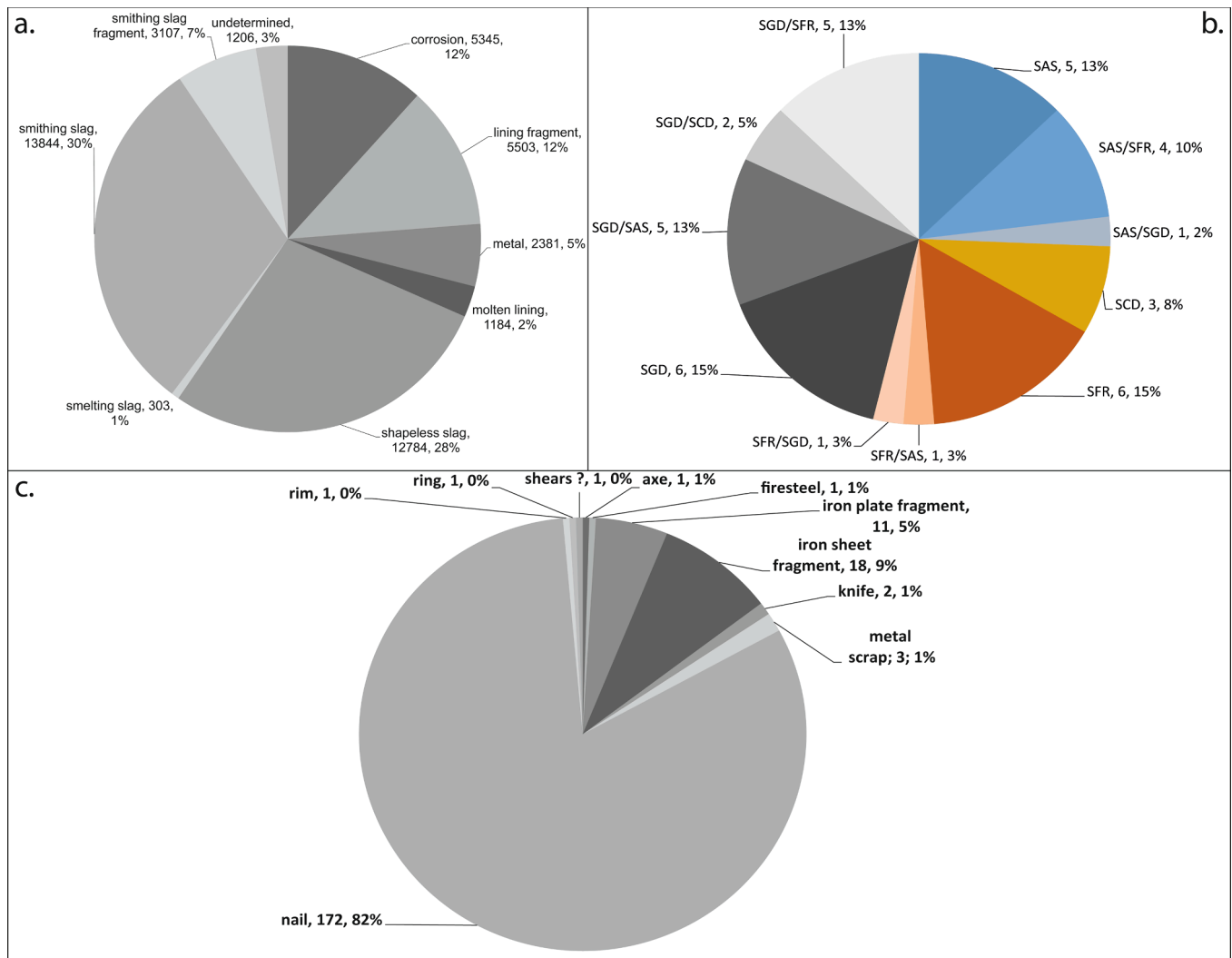


Fig. 2. Summary of the remains of iron working at Oegstgeest, adapted from Disser (2019). a. Proportion of iron working related finds by mass (grams) b. Facies attribution of the slag from Oegstgeest c. Respective proportions of iron finds by mass (grams).

bottoms from Oegstgeest were clustered in contexts associated with either the river or the gullies crossing the settlement, it is possible that the slag was being thrown into the river after each cleaning of the hearth.

In spite of this inability to locate a dedicated workshop, the materials from Oegstgeest have already undergone preliminary macroscopic and typological study, the findings of which are synthesised below (Disser 2019; Theuvs et al., 2021b).

1.2.1. Forge slag from Oegstgeest

Disser (2019) established that 17 kg of the slag from Oegstgeest, about 40 % of the corpus, was forge slag. Three quarters of this slag were small fragments weighing less than 300 g though 39 larger hearth bottoms were also uncovered. Of these, 15 were plano-convex, 4 were biconvex, 4 were faceted, 3 were planar, 2 were concave and 1 was conical. The remaining hearth bottoms were irregular shapes. Average slag length and width were 93 and 70 mm respectively and average thickness was 45 mm. The remaining slag was highly fragmented and amorphous, making it hard to categorise, but a very small quantity (303 g) was identified as possible tap slag due to its flowing and knotted surface. However, this was determined to be too small to ascertain that smelting was taking place on site.

Forge slags are typically split into three different facies based on their macroscopic features which are well established by several French

language studies (see Fig. 5) (c.f. Serneels 1993; Anderson et al., 2003; Serneels & Perret 2003; Eschenlohr et al., 2007). These facies are associated with certain forms of iron working and can give an indication of the types of activities undertaken at a given site. SGD (*Scorie Grise Dense*, dense grey slag) is the most common form of iron slag and results from most forms of iron working. SFR (*Scorie Ferreuse Rouillée*, rusty ferric slag) typically presents a reddish colour, contains large quantities of iron oxides and is associated with high temperature activities resulting in considerable loss of iron into the hearth, such as welding and quenching. The final facies, SAS (*Scorie Argilo-Sableuse*, clay and sand slag) has a glassy aspect, sometimes associated with clay and other sediment. It is associated with use of fluxes and can be an indication of welding. Individual hearth bottoms can be comprised of either one or a stratigraphy of two or more facies, which can give an indication of the sequence of operations during forging.

All three forge slag facies were identified at Oegstgeest with SGD being the most represented in the corpus as 51 % of the slags contain at least some SGD. However, 33 % of the slags also contained SFR with this facies being dominant in 21 %. SAS was present in 36 % of the corpus but was only the dominant facies in 10 hearth bottoms (25 % of the corpus) (see Fig. 2b). In addition, Disser identified a potential fourth facies, which he dubbed SCD (*Scorie Crystalline Dense*, dense crystalline slag) in 13 % of the corpus. This facies is superficially similar to SGD though the hearth bottoms had flat, well-preserved sides, which Disser associated

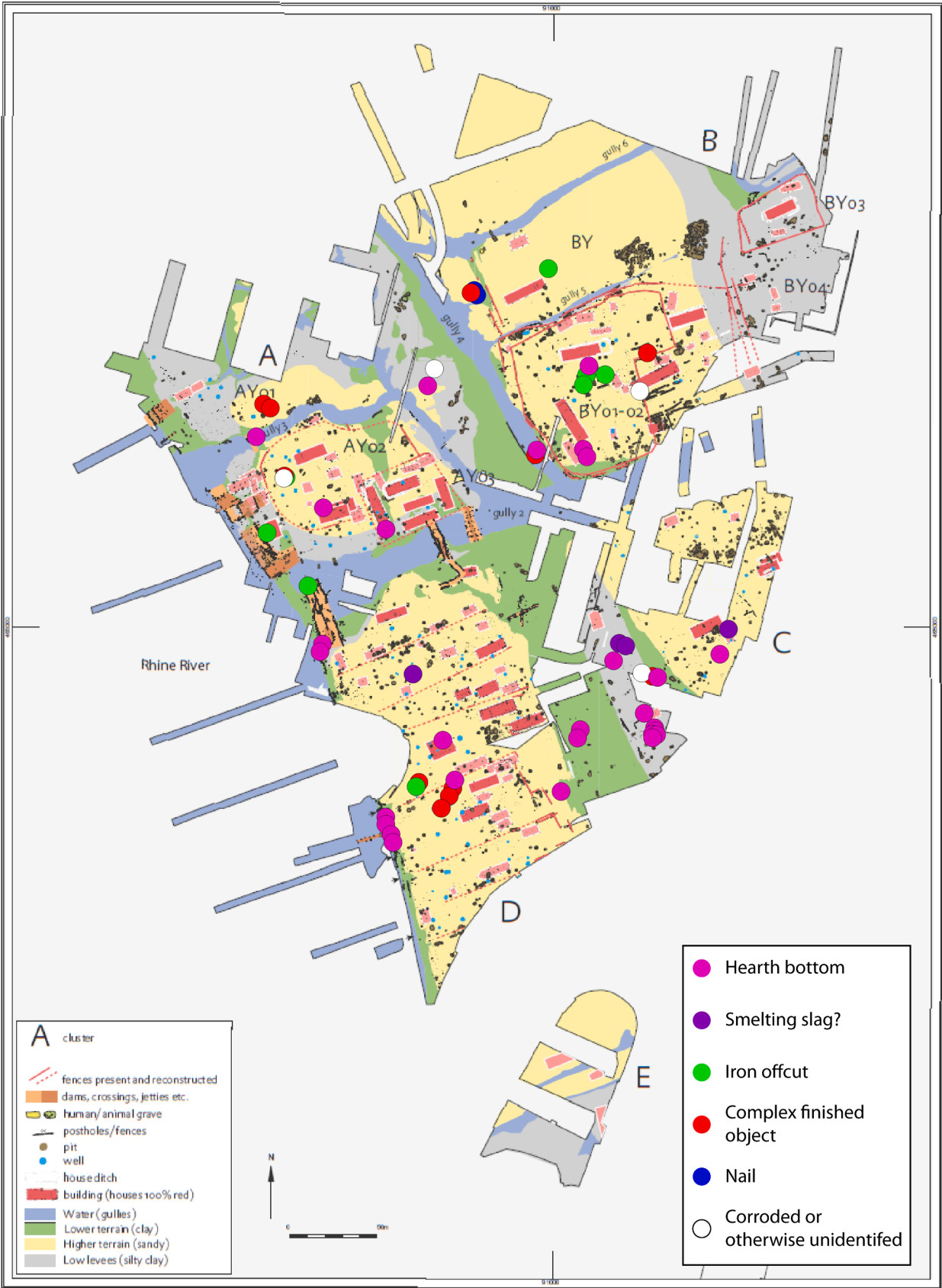


Fig. 3. Location of the ironworking related finds at Oegstgeest.

with the possible presence of macro-crystals.

Finally, [Disser \(2019\)](#) used this information to quantify smithing activities at Oegstgeest. As no dedicated forge was identified, Disser was unable to establish the quantity of iron waste in the relevant contexts and instead based his reasoning on the slag and other scoraceous waste found on site. From this, he found a loss between 9.5 and 12 kg of iron during forging. With careful comparison with similar sites in the literature ([Mangin et al., 2000](#); [Perret 2002](#)) he gave a cautious estimate of 90 to 432 kg of iron objects produced over the lifetime of the site.

1.2.2. Iron finds

In total, 221 iron finds were found at Oegstgeest with nails making up 82 % of the overall corpus (see [Fig. 2c](#)). During excavation, these nails were split into two broad categories, “nails” and “boat nails”, as boat production appears to have taken place on site. This categorisation was established based on the size of the nails, which ranged from 24 to 122 mm in length and from 2 to 9 mm in cross section. Establishing typological categories for the iron finds was difficult as almost all the metal was highly corroded. For this reason, [Disser \(2019\)](#) simply retained the original distinction between “nails” and “boat nails”. The remaining 15 % of iron finds included scrap and other fragments related to forging, as well as finished objects such as knife fragments, a fire striker and an axe head.

From these observations, [Disser \(2019\)](#) concluded that post-smelting activities, specifically object creation and upkeep, were the primary forms of iron working on site, though the small quantity of tap slag could potentially indicate some smelting in the wider area.

1.3. Aims and objectives

With this context in mind, this paper has two aims: to contribute to the existing data on Oegstgeest by providing the first in depth look into the iron working at this settlement, and to use the lens of iron working at Oegstgeest to contribute to the discussion surrounding the role of such sites within their wider socio-economic context.

To reach these goals, this paper sets the following objectives. Firstly, to establish the forge techniques used at Oegstgeest. Secondly, to try and establish the provenance of the iron used at Oegstgeest. Finally, to consider the implications of these results on the nature of iron working at Oegstgeest. The answers to these questions will be used to consider the role of the settlement as a place of iron working in the Early Medieval Netherlands.

2. Methodology and materials

2.1. Assemblage

Of the remains of metalworking at Oegstgeest, 32 finds were selected for this study (see [Table 1](#), [Figs. 4 and 5](#) and the full description of iron and slag finds in the [supplementary material](#)). Among the slag, 15 hearth bottoms were chosen, including at least one instance of each of the four facies identified by [Disser \(2019\)](#). Additional hearth bottoms were chosen to reflect the distribution of facies at Oegstgeest, with complete hearth bottoms being privileged. This was complemented by three pieces of amorphous slag, one of which was found in the same context as one of the hearth bottoms. The remaining two were selected in the hopes of characterising an unidentified surface deposit. Due to the generally poor condition of the metal finds from Oegstgeest, iron samples were selected on two criteria: that they had not already been selected for museum display and their likelihood of containing metallic iron. No X-ray imagery was performed, and the latter criterion was instead established by magnet response and apparent density. Thirteen iron finds were chosen for the final corpus: 8 nails (including 2 boat nails), 2 pieces of forge scrap to characterise the smithing activities, 2 complex objects in the hopes that these might reveal advanced forge techniques that may have taken place on site and 1 unidentified sample. The results of the

Table 1

List of iron and slag finds from Oegstgeest, specifying whether they were included for SEM-EDX analysis and LA-ICP-MS.

Sample N°	Material	Category	Comments	OM	SEM	ICP-MS
164	Metal	Bent nail or possibly bar		Yes	Yes	Yes
180A	Metal	Uncertain, possibly piece of bloom		Yes	Yes	Yes
180B	Metal	Nail		Yes	Yes	Yes
221	Metal	Nail, or possibly chisel	Possibly modern	Yes	Yes	Yes
435	Metal	Nail		Yes	Yes	Yes
586	Metal	Forge scrap		Yes	Yes	Yes
968 sub 1	Metal	Fire striker		Yes	Yes	Yes
968 sub 2	Metal	Uncertain, possibly knife blade		Yes	Yes	Yes
968 sub 3	Metal	Nail		Yes	Yes	Yes
2540	Metal	Nail		Yes	Yes	Yes
2546	Metal	Nail		Yes	Yes	Yes
2611	Metal	Nail		Yes	Yes	Yes
5355	Metal	Small bar		Yes	Yes	Yes
196 sub 3	Slag	SGD/SAS		Yes	Yes	No
226	Slag	Hearth bottom SGD/SCD		Yes	Yes	No
283A	Slag	Hearth bottom SFR		Yes	Yes	No
283B	Slag	Hearth bottom SCD		Yes	Yes	No
603	Slag	Hearth bottom SFR		Yes	Yes	No
662	Slag	Hearth bottom SFR		Yes	No	No
727	Slag	Hearth bottom SAS		Yes	No	No
2001 sub 2	Slag	Hearth bottom SCD/SGD	Double hearth bottom	Yes	Yes	No
2001 sub 6	Slag	Hearth bottom SAS	Double hearth bottom	Yes	Yes	No
2011A	Slag	Hearth bottom SFR		Yes	Yes	No
2011B	Slag	Amorphous SFR		Yes	No	No
2014	Slag	Hearth bottom SFR		Yes	Yes	No
2487	Slag	Hearth bottom SGD		Yes	No	No
2526	Slag	Hearth bottom SFR		Yes	No	No
3156	Slag	Hearth bottom SFR		Yes	No	No
5047	Slag	Amorphous SGD/SAS	Unusual surface deposit	Yes	Yes	No
5052	Slag	Amorphous SGD/SAS	Unusual surface deposit	Yes	Yes	No
5161	Slag	Hearth bottom SFR		Yes	No	No
5763	Hearth lining	Large piece of vitrified tuyère		Yes	No	No

study of the iron and slag is synthesised in [Tables 3 and 4](#) respectively.

2.2. Sample preparation

Sample preparation was based on similar studies ([Pagès 2011](#); [Disser et al., 2016](#); [Berranger et al., 2017](#); [Disser et al., 2020](#)). The slag samples were cut using a Struers Unitom-2 circular saw. The iron samples were cut using a Struers Accutom-50 saw along their length to provide an

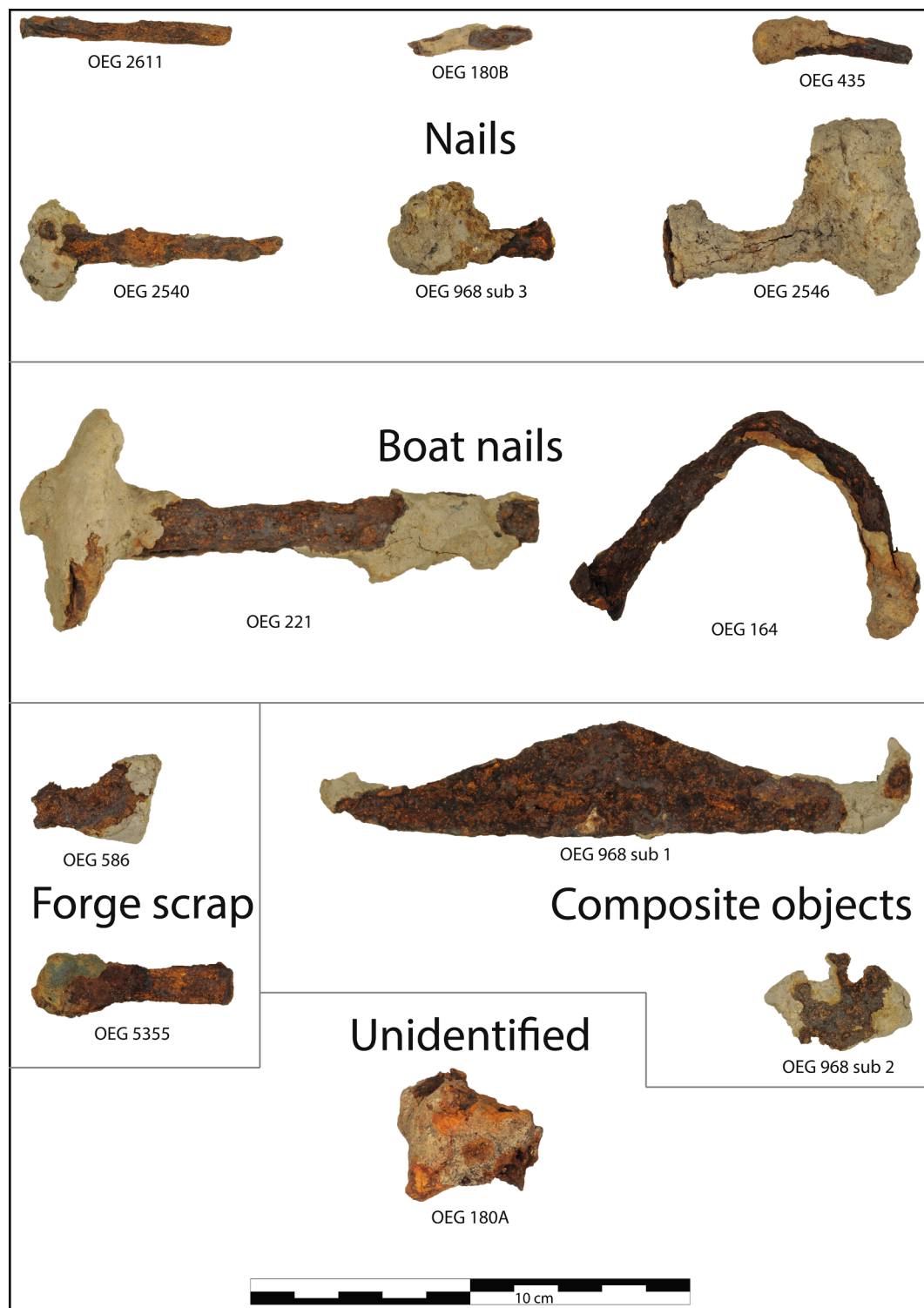


Fig. 4. Overview of the iron finds from Oegstgeest.

overview of the piece. Two larger samples (OEG 164 and 221, boat nails) had approximately 1.5 cm cut from the end, which was then cut in half. OEG 968 sub 1 (fire striker) had two triangular sections removed at different heights to examine the full width of the piece while preserving its structural integrity. Once cut, the larger samples were embedded in Struers EpoFix epoxy resin and smaller samples (>2 cm in length) were embedded in transparent acrylic under pressure for five minutes using a Metkon Ecopress 52. The resulting samples were polished using abrasive disks and diamond solution (grade P80 paper to 1 μ m diamond solution)

to obtain a mirror finish.

2.3. Analytical approach

2.3.1. Optical microscopy

Metal samples were etched first using Nital (4 vol% HNO₃ in ethanol) then polished and etched again using Oberhoffer's reagent (micrographs of all samples are available in the [supplementary material](#)). In both cases, the surface was studied by reflected light microscopy

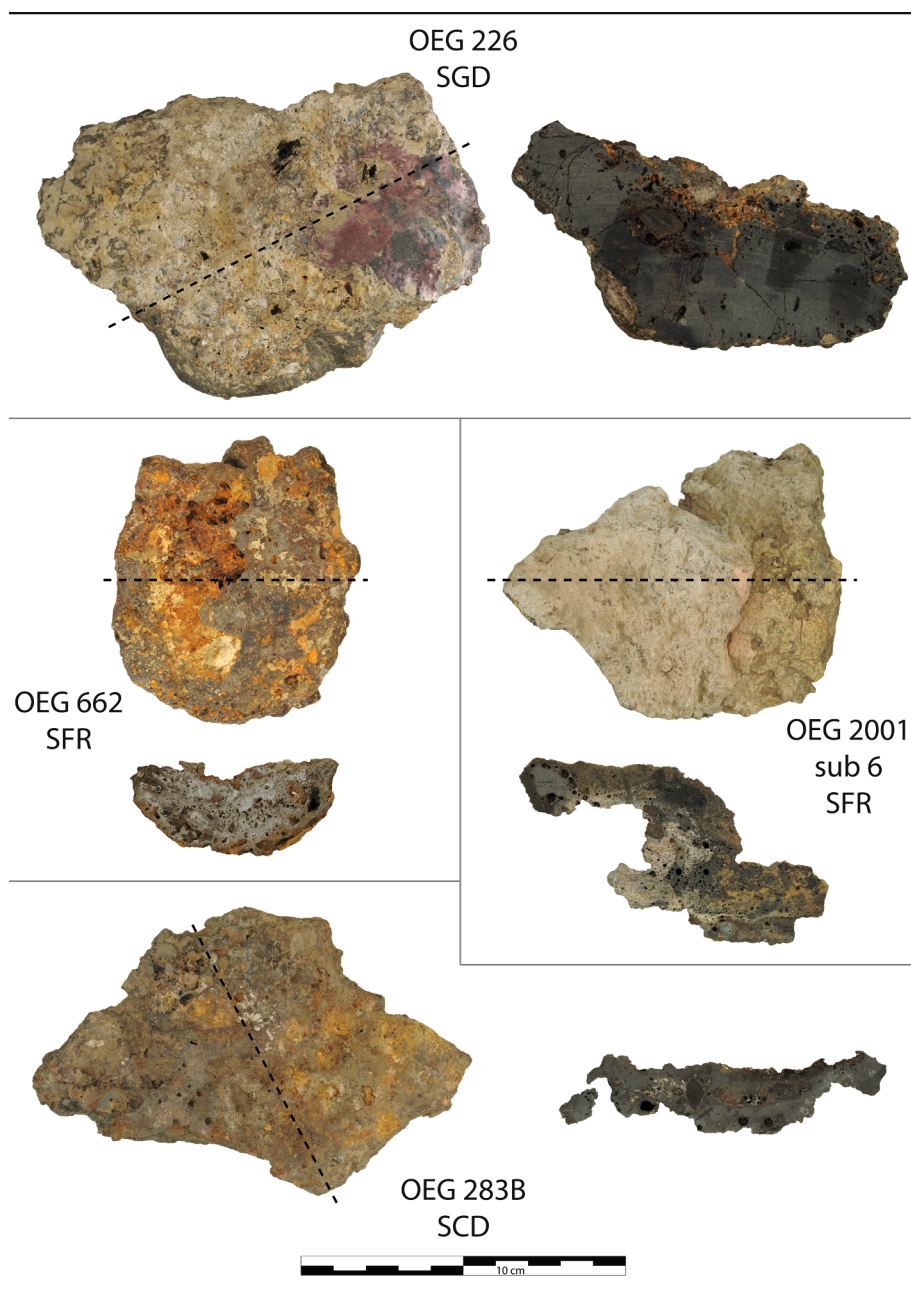


Fig. 5. Overview of the slags from Oegstgeest.

using a Zeiss Axio Imager A2 Vario. Low magnification micrographs were taken across the surface of the sample using a Zeiss Axiocam camera. These were assembled to create a mosaic image of the surface microstructure using Zen Core v. 3.3. Areas typical of the microstructure of the sample, as well as any areas of metallurgical interest were photographed. The proportion of pearlite was used to establish the approximate carbon content of each sample (c.f. [Pagès 2011](#); [Gosselin 2021](#)). Slag samples were analysed and photographed using the same setup to establish mineral compounds present within the slags.

2.3.2. SEM-EDX

A 20 nm carbon coat was applied to the samples, which were then subjected to elemental analysis by energy dispersive X-ray spectrometry coupled with scanning electron microscopy. This was accomplished using a JEOL SEM-FEG 7001 equipped with a silicon-drift detector with the setup and protocol modelled on that of prior papers on similar topics

([Leroy et al., 2012](#); [Disser et al., 2016](#); [Dillmann et al., 2017](#); [Disser et al., 2020](#); [Pagès et al., 2022](#); [L'Héritier et al., 2023](#)). Accelerating voltage was set at 15 kV, working distance at 10 mm and probe current around 8nA. This allows for reliable quantification of elements over 0.3–0.5 wt %, depending on the element in question. An automated filter was applied to each spectrum to remove the background noise.

Quantification of chemical elements was processed using XPP matrix correction routine (with a Phi-Rho-Z function). O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe and Cu were systematically quantified, and results were normalised to 100 %. The iron samples were studied using the same protocol as [Disser et al. \(2020\)](#): slag inclusions in the iron matrix were systematically analysed by backscattered-electron imagery using $\times 300$ magnification. This process generated a spreadsheet detailing spatial (location, size, and shape) and chemical data for each identified particle. This was used to complement the metallurgical study as it allows the differentiation of forge and smelting inclusions, as well as

identifying areas made from separate blooms (c.f. [Disser et al., 2020](#)).

Slag samples containing a microstructure seen in all or most of the respective slag facies (SGD, SAS, SFR and SCD) were also analysed by SEM-EDX. Additional SEM-EDX analysis was performed on slag samples containing phases that were unable to be identified by optical microscopy. A 2 cm² sample of the area of interest was identified using optical microscopy and sampled using a Brot geological saw. These were then re-embedded in Struers EpoFix resin, carbon coated and analysed using the pre-established parameters combined with the cartography tool in Aztec. Synthesis of the results of the study of the iron and slag are presented in [tables 3 and 4](#) respectively.

2.3.3. LA-ICP-MS

Establishing possible origins for the iron used at Oegstgeest was based on trace element content in slag inclusions. This was quantified by Laser Ablation Inductively Coupled Plasma Mass Spectrometry at the IRAMAT Centre Ernest Babelon in Orléans. Set up and methodology was modelled on that used by [Bérard et al. \(2020\)](#), itself based on the protocol detailed in [L'Héritier et al. \(2016\)](#). Measurements were performed using a sector field Thermo Scientific ICP-MS Element XR coupled with an ArF* excimer laser ($\lambda = 193$ nm, RESolution S155-E, Resonetics). Beam diameter was set at 80 μ m with a pulse duration of 4–5 ns and a repetition rate of 7 Hz. Energy rate was 34 μ J per pulse. The ablated particles were carried to the plasma torch using an Ar/He carrier gas (1.01 L·min⁻¹) which was used to form the plasma. Cooling gas flow rate was 16 L·min⁻¹ with an auxiliary gas flow rate of 1 L·min⁻¹. Measured isotopes were: ⁹Be, ²⁸Si, ⁴⁷Ti, ⁵¹V, ⁶⁰Ni, ⁶³Cu, ⁶⁹Ga, ⁷²Ge, ⁷⁵As, ⁸⁵Rb, ⁸⁸Sr, ⁸⁹Y, ⁹⁰Zr, ⁹³Nb, ¹¹⁸Sn, ¹³³Cs, ¹⁷⁸Ba, ¹³⁹La, ¹⁴⁰Ce, ¹⁴¹Pr, ¹⁴⁶Nd, ¹⁴⁷Sm, ¹⁵³Eu, ¹⁵⁷Gd, ¹⁵⁹Tb, ¹⁶¹Dy, ¹⁶⁵Ho, ¹⁶⁷Er, ¹⁶⁹Tm, ¹⁷²Yb, ¹⁷⁵Lu, ¹⁷⁸Hf, ¹⁸¹Ta, ¹⁸²W, ²⁰⁸Pb, ²³²Th and ²³⁸U. Time per sample was 10 ms with 100 samples per peak. Due to the varying size of slag inclusions, the quantity of ablated material was a function of inclusion size so the net-recorded signal for each trace element was normalised using ²⁸Si as an internal standard. This was measured using Faraday detection mode with a segment duration of 100 ms. All other isotopes were measured using triple detection mode with a segment duration of 40 ms.

The samples were placed in ablation cells alongside a NIST610 standard reference glass for calibration. [Bérard et al. \(2020\)](#) found this to be the closest approximation to slag inclusions. At the start of each session, a blank signal was obtained for 20 s to measure the background noise. The NIST610 was then measured 3 times followed by 18 measurements of the archaeological samples, after which this process was repeated. Once all samples were analysed, a final blank and 3 measurements were performed on the NIST610. In total, 12 slag inclusions per sample were selected for analysis. The goal was to choose inclusions representative of the sample as a whole, so the choice of slag inclusions was informed by the results of SEM-EDX analysis: for samples made from multiple blooms, an equal number of inclusions were chosen on both sides of the weld line. Large slag inclusions were preferred to limit accidental ablations of the metal matrix.

2.3.4. Raman spectrometry

The study of OEG 180A revealed inclusions that were unable to be fully characterised by optical microscopy or SEM-EDX analysis. These were further studied using Raman spectrometry to establish the precise mineral compound. This was accomplished using a Renishaw Invia Reflex spectrometer equipped with a doubled Nd-YAG laser $\lambda = 532$ nm) and a Leica DMLM microscope using a $\times 50$ lens to focus the beam on the sample surface. A silicon reference wafer was used for calibration with the reference peak at 520 cm⁻¹. Spectral resolution was on the order 2 cm⁻¹ and power was limited to under 100 mW to avoid heating the surface and affecting sample composition. Beam area was set to around 1 μ m². Spectra were obtained from five 30 s acquisitions over the inclusion and five 30 s acquisitions over the metallic matrix. The signal from the metallic matrix was then subtracted from the inclusion signal. Spectrum acquisition was performed in Wire 3.4 and the baseline was

established using the included Cosmic Ray Remover software. Data processing was undertaken in Origin Pro 2016. The obtained spectra were compared with published reference spectra ([Weber et al., 2015](#)).

2.4. Data processing

Due to the large quantity of data produced by SEM-EDX and LA-ICP-MS, data processing was performed using programs written by Alexandre Disser ([Disser et al., 2016; 2020](#)). Because of the effect that differences of magnitude can have on descriptive multivariate analyses when applied in Euclidian space, the data underwent an initial transformation to limit this impact. The log ratio has been found to be the most effective method of data transformation for slag inclusions in archaeological iron; specifically a transformation to X_{ij} values ([Charlton et al., 2012; Leroy et al., 2012](#)). The transformation is calculated using the following formula:

$$X_{ij} = \log_{10}([E]) - \frac{1}{N} \sum_{k=1}^N \log_{10}([E_k])$$

Where $[E]$ is the measured quantity of each element in a given inclusion and $[E_k]$ is the quantity of each of the selected elements.

For major element data, values with a standard deviation over 10 % the measured value were removed though the small number of inclusions in OEG 968 sub 2, 2540, 2546 and 5355 required this limit to be raised to 50 % for these samples. The remaining entries were converted to oxide values (assuming iron was present under valance II) and converted to X_{ij} values. The resulting data was run through a Hierarchical Clustering Analysis (HCA) to sort entries into classes based on chemical similarity (see [Husson et al., 2010](#)). A threshold of chemical similarity was decided by the user upon study of the resulting dendrogram. This was unique to each sample and chosen to best reflect the data. Samples with a common branch below this threshold were placed in the same group while samples with a common branch above the threshold were placed in separate groups. The results were plotted over the mosaic of the sample surface, which allowed easy identification of zones within the sample with differing inclusion chemistry. The resulting data was run through a Principal Component Analysis (PCA) to convert the results into Cartesian coordinates. The full results are available in the [supplementary material](#).

2.5. Provenance

2.5.1. Provenance attribution

Provenance was established by direct comparison of trace element content of slag inclusions with smelting slag and iron ore of known origin. This method requires consistent concentrations of elements between ore, slag, and slag inclusions. As such, not all elements detected by LA-ICP-MS are usable. Some elements (known as *siderophiles*) preferentially bond with the iron during the smelt and are therefore over-represented in the metallic iron. LA-ICP-MS analysis often accidentally ablates a small portion of the iron matrix meaning that any provenance attribution relying on *siderophile* elements will be skewed by this over-representation. In addition, some elements can show excessive variance even after conversion to X_{ij} values. The choice of elements for this study was based on the findings of [Leroy \(2010\)](#) and [Disser \(2014\)](#): Y, La, Ce, Yb, Nd, Pr, Gd, Sm, Dy, Eu, Th and U.

This study follows the example of [Disser et al. \(2016\)](#) and uses an unsupervised method of data analysis. Such methods of data analysis allow a categorisation based directly on chemical data: samples are ranked by chemical similarity and the obtained data is then reviewed manually to establish groups that best reflect the samples. The method of analysis chosen for this study was Hierarchical Clustering of Principal Components (HCPC, c.f. [Husson et al., 2010](#)). Once converted to X_{ij} values, a preliminary PCA was performed to “de-noise” the dataset. The results were run through an HCA, which was the primary method of

establishing provenance. Provenance attribution was the same as group attribution for the major elements: if two analyses were attributed to a common branch of the resulting dendrogram below the user-defined threshold, they were assumed to have a common origin. Finally, the results underwent a second PCA to represent the data in Cartesian coordinates.

Provenance was established in two stages. No method of analysis can account for the entirety of chemical variation of slag produced from a single source of ore. As such, a direct comparison of inclusions from Oegstgeest with the ore and slag could result in confusion due to several inclusions from a single sample being attributed to distinct sources. For this reason, an initial “intra-site” comparison was undertaken between the Oegstgeest samples without including the ore and slag to establish whether any samples had a common origin. As the “height” values provided by the HCA are indicative, ensuring a meaningful contrast required including a sample known to be of a different origin (in this case a shaped offcut from Messein in Lorraine c.f. [Disser 2014](#)). The second “inter-site” stage involved individual comparisons between each sample and the full corpus of analyses of ore and slag of known origin. However, initial runs rarely matched samples with single sources so any potential match underwent the same process a second time, including only the entries grouped in the first run. The results of this comparison were synthesised [Table 5](#) and are presented in full in the [supplementary material](#).

2.5.2. Selected ore and slag for comparison

Analyses of ore and slag were chosen on the likelihood of a connection with Oegstgeest (see [Fig. 6](#)). As detailed previously, the Netherlands, particularly the Veluwe, are a likely candidate for the iron used at Oegstgeest. However, while ore and slag from the Veluwe has been extensively studied ([Joosten 2004](#)), the available data focuses on siderophile elements. Due to the aforementioned risk of over-

representation of these elements, the data from the Veluwe is currently incompatible with the methods of this study. As such, while the Veluwe was not included, it was borne in mind as a possible origin for otherwise unattributed samples.

The samples that were included (detailed in [Table 2](#)) came from regions in the broader Rhine and Meuse River systems. In particular, this included entries from Condroz in southern Belgium, characterised by [Pagès et al. \(2022\)](#), who differentiated between slag from Eastern Condroz and Entre-Sambre-et-Meuse in Western Condroz. This differentiation was due to the latter area extending into regions that contained no iron ore but did contain some smelting sites. Additional samples came from Lorraine in Eastern France, based on ore and slag characterised by [Disser et al. \(2016\)](#). Iron production in Lorraine relied on a wide range of metallogenic contexts, different kinds of sedimentary ore, as well as siderolithic and vein ores. Two provenance spaces described by [Disser et al. \(2016\)](#) were not included. The Bajocian-Bathonian ore corresponded to material from only two sites and the ore and slag from St-Dizier was characterised by only one site. These were determined to be too small to be sufficiently representative and were not included to avoid skewing the results of the provenance study.

The final samples included in this study come from across Southern Germany, characterised by [Dillmann et al. \(2017\)](#). This region was included in part due to its proximity to the Rhine River, but also because of the connection between the Rhine and Danube rivers in the Early Middle Ages. At this period, these rivers formed a major axis of transportation between Eastern and Western Europe ([van Es & Verwers 2010](#)). Given the aforementioned contact established between Oegstgeest and the Mediterranean by [Theuvs et al. \(2021a\)](#), it is likely that the objects traded between these regions took this route. As such, data from Southern Germany, the land between the Rhine and Danube rivers, as well as one of the best characterised provenance spaces in the region, was a pertinent candidate for this study.

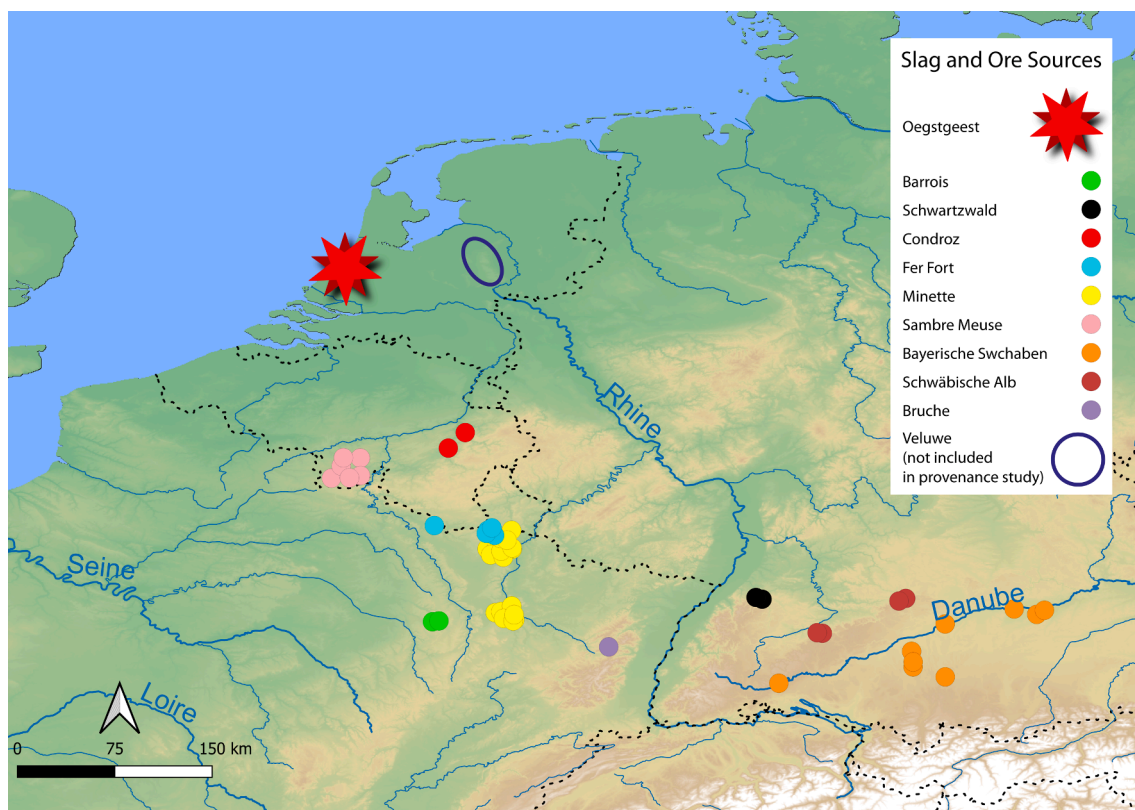


Fig. 6. Map showing the origin of the ore and slag chosen for the provenance study as well as the Veluwe.

3. Results

3.1. Slag samples

The mineral facies identified by Optical Microscopy in the slags from Oegstgeest match similar examples described in the literature. SGD slag was comprised of fayalite with widespread presence of wüstite dendrites (see Fig. 7a). SFR was made of fayalite and globular wüstite as well as large quantities of other iron corrosion products that were unable to be identified (see Fig. 7b). SAS slags showed vitrified microstructures with occasional iron prills caught in the glassy matrix (see Fig. 7c). The SCD facies identified by Disser (2019) was indistinguishable from SGD as it was also comprised of fayalite with wüstite dendrites, though these hearth bottoms did appear to contain more spinels (see Fig. 7d). Subsequent SEM-EDX analysis found that these were all iron oxides at concentrations consistent with magnetite. There was one exception to this trend as OEG 283B presented a different microstructure. Macroscopically, the slag was a complete circular hearth bottom with a thin cross section (~2 cm). Rather than the ubiquitous fayalite and wüstite observed in other slags, its microstructure was dominated by spinels and needle like crystals (see Fig. 8). SEM-EDX analysis found many of these to be comprised of Oxygen, Iron and Aluminium, suggesting that these are hercynite. However, other minerals identified in the same slag either did not contain iron, or contained higher concentrations of Magnesium and Calcium, suggesting the presence of a wide range of minerals in this hearth bottom.

Several slag samples contained clear strata between different slag facies, and this was especially noticeable in OEG 5047 and 5052. These

slags were not hearth bottoms and were included for analysis in the hopes of identifying an unusual blue surface deposit. Their microstructure was almost identical with both comprised of a lower SGD stratum and an upper SAS stratum, which contained the blue colouration. Furthermore, optical microscopy identified a beige surface deposit adhering to the SGD strata in both slags (see Fig. 9). SEM-EDX analysis found this deposit to be an iron sulphide, seemingly the same in both samples, possibly pyrite (FeS_2). The lower SGD strata contained fayalite and wüstite dendrites though the latter presented unusually angular edges, not noted in any of the other slags. This could indicate that the wüstite is euhedral. Despite the blue colouration, optical microscopy was unable to distinguish between these SAS strata and other such examples from Oegstgeest, though SEM-EDX did find higher concentrations of calcium in OEG 5047 and 5052.

The last slag of note was OEG 603, a hearth bottom initially identified as SAS due to the sediment adhering to its surface. Observation of the cross section and optical microscopy found it to be consistent with SGD ("rusty" appearance, presence of fayalite and globular wüstite alongside iron corrosion product). SEM-EDX analysis also found the glassy matrix surrounding these minerals to contain unusually high concentrations of Mn (up to 11.28 wt%). In addition, the hearth bottom contained several green prills (~1 mm diameter, see Fig. 10). SEM-EDX analysis found these to be copper oxides. One of these prills was found encircling another and both presented an enrichment on their surfaces with elements common in slag (Fe, Si and Al). Further analysis by SEM-EDX found smaller metallic copper prills (~1 μm diameter) in the sediment adhering to the surface of the slag.

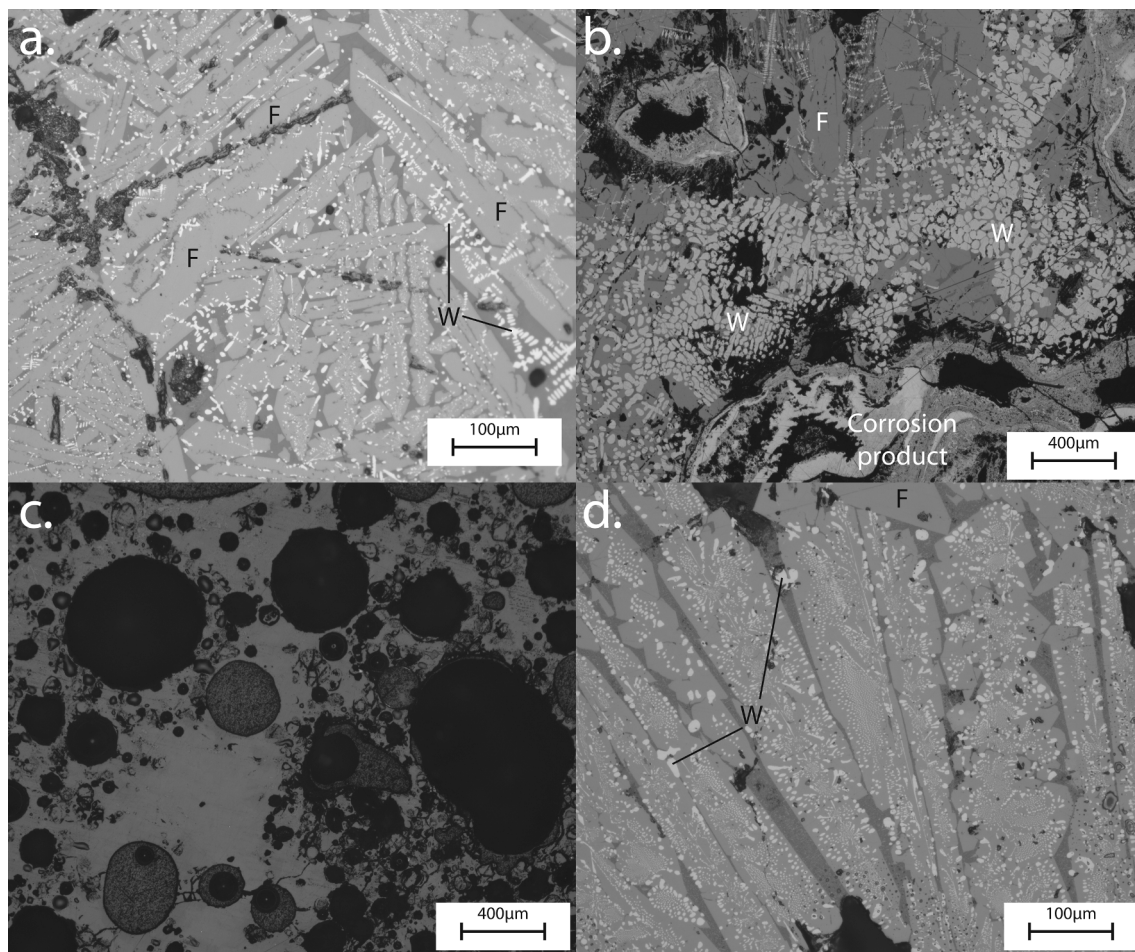


Fig. 7. Microstructure of the slags from Oegstgeest imaged by Optical Microscopy. W. Wüstite, F. Fayalite. S. Spinel. a. OEG 226. A typical example of SGD slag b. OEG 662. A typical example of SFR slag c. OEG 2001 sub 6. A typical example of SAS slag d. OEG 2001 sub 2. One of the SCD slags identified by Disser (2019).

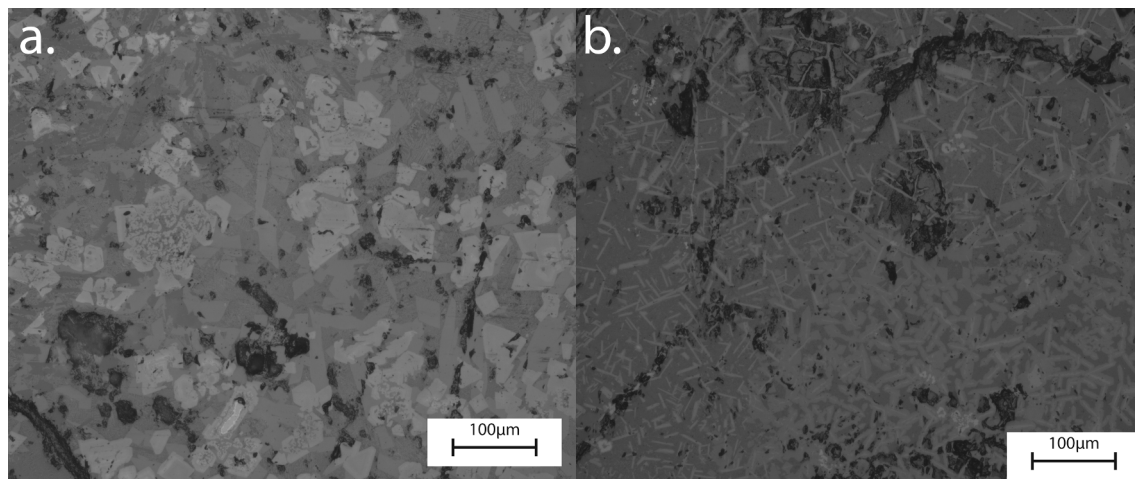


Fig. 8. Microstructure of OEG 283B imaged by Optical Microscopy. a. Spinel rich microstructure. b. Unidentified Needle like crystals.

Table 2

Geological and archaeological data concerning the ore and slag of known provenance selected for the provenance study.

Region	Provenance space	N° of slags	N° of ores	Ore Type	Ore formation period	Site chronology	Source
Wallonia (Belgium)	Eastern Condroz	19	2	Limonite or oxidized sulphide ore	Famennian or Dinantian (c. 371–330 Ma)	La Tène D – Late Antiquity	Pagès et al., 2022
Wallonia (Belgium)	Entre-Sambre-et-Meuse	20	0	Limonite or oxidized sulphide ore	Famennian or Dinantian (c. 371–330 Ma)	La Tène D – Late Antiquity	Pagès et al., 2022
Lorraine (France)	Fer Fort	18	1	Siderolithic ore	Aalenian (176–172 Ma)	Roman-Early Middle Ages and 3 slags undetermined	Disser et al., 2016
Lorraine (France)	Barrois	15	0	Ooid, lithoid and geodic ore	Valanginian (c140–136 Ma)	Roman-Early Middle Ages	Disser et al., 2016
Lorraine (France)	Minette	81	21	Oolitic ore	Aalenian (176–172 Ma)	La Tène-Middle Ages	Disser et al., 2016
						4 slags Undetermined	
						15 slags produced during modern experimentation	
Vosges (France)	Bruche	21	0	Goethite/Magnetite	Buntsandstein (251–245 Ma)	Early Middle Ages	Disser et al., 2016
Southern Germany	Schwarzwald	4	12	Manganese rich limonite	Not specified	Hallstatt D/La Tène A	Dillmann et al., 2017
Southern Germany	Bayerisch Schwaben	18	10	Bog ores	“Post-glacial”	La Tène B-D	Dillmann et al., 2017
Southern Germany	Schwäbische Alb	11	9	Various, often limonitic	Not specified	La Tène A-Medieval	Dillman et al. 2017

3.2. Metal samples

3.2.1. Nails

No clear distinction was established between the nails and boat nails, either by optical microscopy or major element HCP. Both boat nails had relatively low carbon content with OEG 164 being ferrite with some patches of hypo-eutectoid steel and OEG 221 being entirely ferrite. No welds were identified in either sample as the entirety of slag inclusions were attributed to a single chemical group. These same features were observed in almost all the other nails and are consistent with standard bloomery steel. The only exception was OEG 2611, which was a mixture of ferritic iron and hypo-eutectoid steel but contained a weld identified by major element HCP (see [Fig. 11](#)). Inclusions on either side of the weld line were attributed to separate groups, suggesting the use of multiple blooms. Etching with Oberhoffer's reagent revealed ghost structures in all but one of the nails (OEG 2540) indicating the use of phosphoritic iron (see [Fig. 12](#)). The extent of these structures varied considerably from sample to sample, from a minimal presence in OEG 180B to extensive structures across the entire sample in OEG 2546. The

microstructure across two of the nails (OEG 968 sub 3 and 2540) was very even which would suggest similarly even carbon distribution across the piece (see [Figs. 13 and 14](#)).

Two nails (OEG 180B and 2540) presented an unusually high copper content in several of the slag inclusions. SEM-EDX analysis found similar high copper content in both the slag and iron samples but in most cases, these could be discounted as either instrument error (as indicated by the high variance of the respective analyses) or accidental measurement of the copper tape used to complete the circuit within the electron microscope. However, the presence of copper in these samples was confirmed by LA-ICP-MS.

3.2.2. Forge scrap

The two pieces of forge scrap presented very different microstructures; OEG 583 (offcut) was entirely ferrite with equiaxed grain (~200 µm diameter). The piece showed a clear uptick on one end, characteristic of an offcut ([Anderson et al., 2003](#)). In contrast, OEG 5355 (bar) presented a mixed microstructure: two bands of ferritic iron surrounding a central band of steel ([Fig. 15](#)). The low proportion of inclusions in this

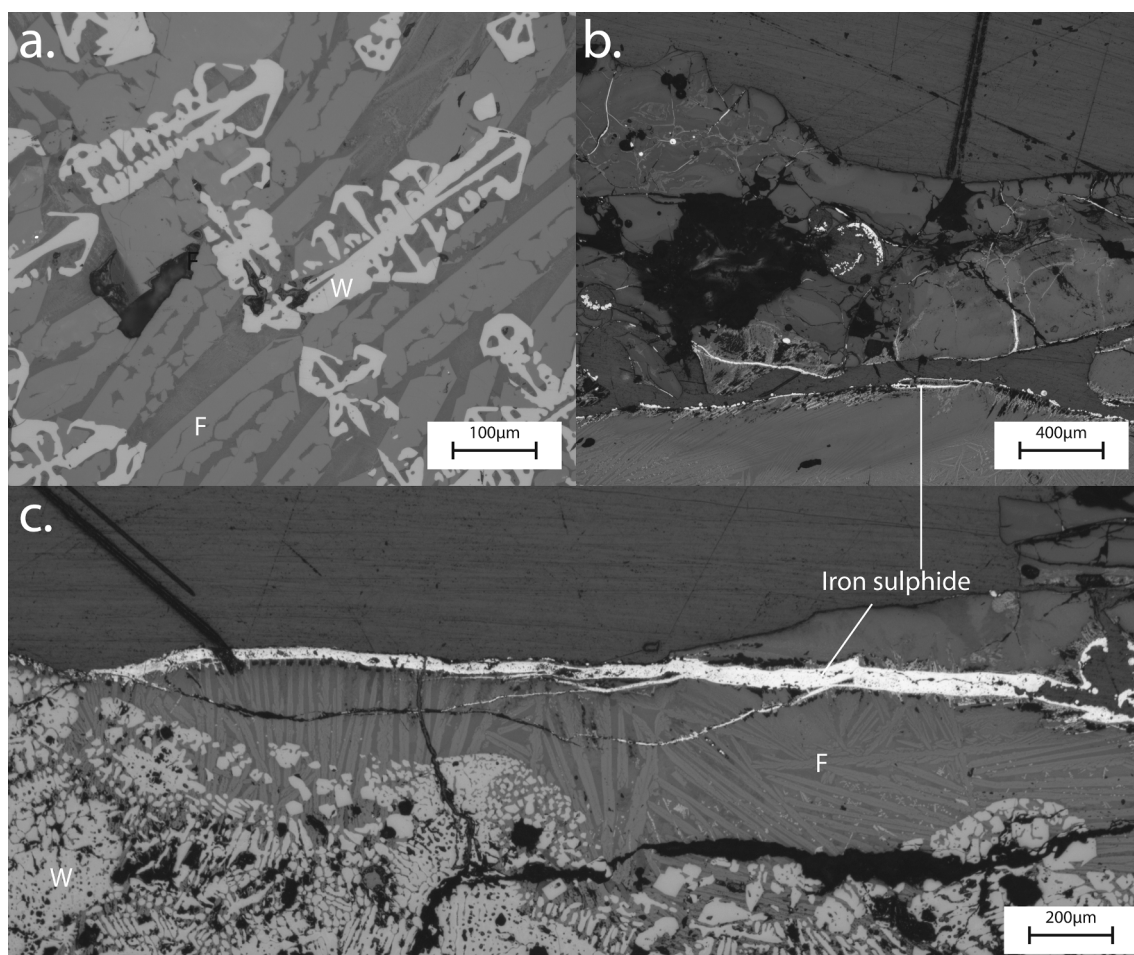


Fig. 9. Overview of OEG 5052. a. Euhedral wüstite. b. Upper SAS stratum. c. Iron sulphide deposit on the slag surface.

sample (only 2.3 % of the sample surface, most of which were corrosion product) made meaningful attribution of inclusions to chemical groups by HCP difficult. The forge inclusions along the weld were attributed to a separate group but there were too few inclusions in the rest of the sample to effectively interpret the data. The presence of a weld in this sample is evident from optical microscopy though it is uncertain whether the iron was folded around a steel core or if two separate pieces of iron were used. The Oberhoffer etch found ghost structures in the upper ferrite band of OEG 5355, making it the only non-nail to present such structures (see Fig. 12c). This same section showed a mixture of fine grain ferrite with bands of hypo-eutectoid steel. The lower ferrite section was entirely large grain with no carbon structures visible from nital etching. The central band was eutectoid steel with a slight decrease in carbon content along the centre (see Fig. 5).

3.2.3. Composite objects

OEG 968 sub 2 (possible knife fragment) contained a very small number of slag inclusions, covering only 0.5 % of the sample surface. However, the most prominent of these inclusions formed a line along the centre of the sample. This same zone corresponded to a faded line in the Oberhoffer etch, suggesting a weld. This was confirmed by the major element HCP as the inclusions in this zone were attributed to a distinct class (see Fig. 16). The entire sample was eutectoid steel, verging on hyper-eutectoid and presented a highly homogeneous microstructure.

OEG 968 sub 1 (fire striker) had the highest carbon content of any sample as the entire piece was either eutectoid or hyper-eutectoid steel (See Fig. 17a). The spine and the working edge were separated by a long series of inclusions that appear to run the length of the sample. These were attributed to a distinct class by the major element HCP due to

differences in Mn and Na content (see Fig. 18). However, in spite of their central location between the spine and working edge, these inclusions do not appear to be a weld. Their large size, lack of wüstite and elongated rather than globular shape all indicate that these are smelting inclusions. The entire working edge of the sample presented martensitic structures, indicating that the piece had undergone a differential quench. However, a section of the working edge presented cementite grain boundaries (see Fig. 17b and c).

3.2.4. Unidentified sample

OEG 180A was neither a finished object nor forge scrap; it was entirely ferrite though without a clear grain structure. Instead, the ferrite had a globular appearance and disaggregated into the extensive inclusions (29.8 % of surface) as well as into patches of the slag gangue that adhered to the surface. This sample contained very few silicon rich slag inclusions, as seen in the other samples, and instead contained spherical beige inclusions that were unable to be identified by OM (see Fig. 19). SEM-EDX analysis found that these were iron sulphides (67 wt % Fe and 33 wt % S). Additional characterisation was undertaken by Raman spectrometry. The resulting spectrum was unclear and lacked the characteristic peaks of iron sulphides between 250 and 300 cm^{-1} , though these results are consistent with pyrrhotite (Fe_7S_8) (see Fig. 20). However, the lack of resolution in this spectrum, combined with the measured Fe and S content being different than the predicted values for pyrrhotite (60.4 wt% Fe and 39.6 wt% S) indicate that multiple iron sulphides are likely present.

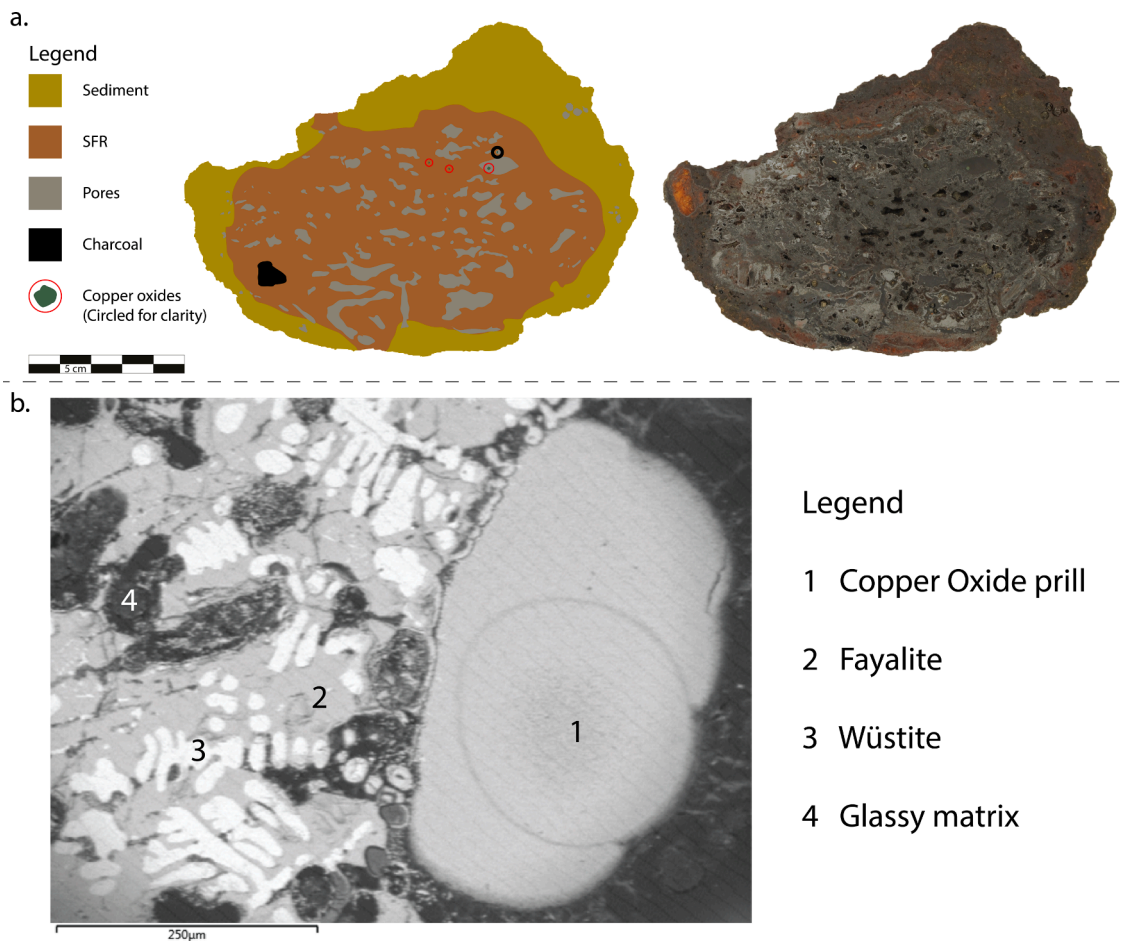


Fig. 10. Microstructure of OEG 603. a. Cross section of OEG 603 showing the distribution of the different facies and the presence of copper oxide prills. b. Back-scattered electron imagery of the double copper prill seen in OEG 603 (circled in black in Fig. 6a).

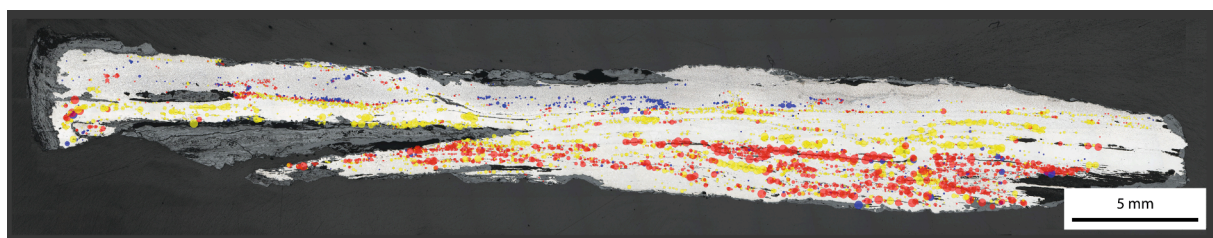


Fig. 11. Chemical groups of inclusions of OEG 2611 established by HCP plotted over a micrograph of the sample surface. Three clear groups of inclusions were established in this sample, represented by points of different colours, revealing the use of at least pieces of iron made from different blooms welded together.

3.3. Provenance

3.3.1. Intra-site comparison

The first attempt at intra-site comparison found that the inclusions from OEG 180A were split across multiple chemical groups, indicating highly heterogeneous inclusion chemistry across the sample. For this reason, this sample was removed from the intra-site comparison to avoid skewing the overall results. Intra-site comparison established 7 groups though the high chemical similarity of inclusions within individual samples could indicate that each sample should be attributed to individual groups (see Fig. 21). The only sample to be attributed to two separate groups was OEG 968 sub 2, which is unsurprising in light of the weld identified by major element HCP in this sample. A quarter of the

inclusions from this sample matched with OEG 2611 and 5355, meaning that the resulting group contained most entries from samples known to contain forge inclusions. Subsequent visual confirmation by optical microscopy found that the respective ablations were overwhelmingly performed on forge inclusions, meaning that these were unfortunately not usable in the provenance study.

3.3.2. Inter-site comparison

Individual comparison of finds against the full range of candidate provenance spaces found very few clear groupings of slag inclusions from Oegstgeest with these sources. Only three samples were placed in a common group with entries other than those from the same sample. Two samples, OEG 221 and 435, which were grouped together by the intra-

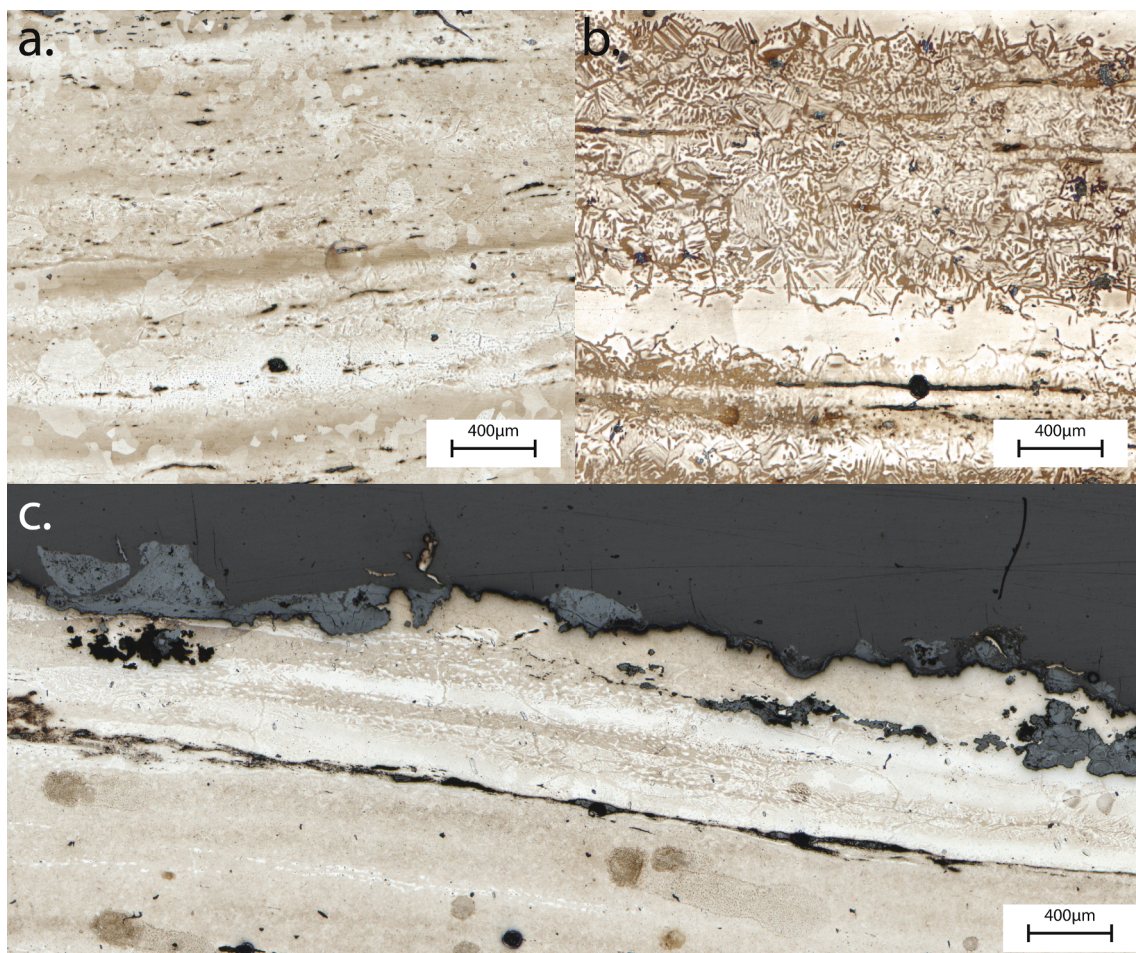


Fig. 12. Ghost structures seen in the samples at Oegstgeest. a. OEG 221 (nail). b. OEG 2546 (nail). c. OEG 5355 (offcut).

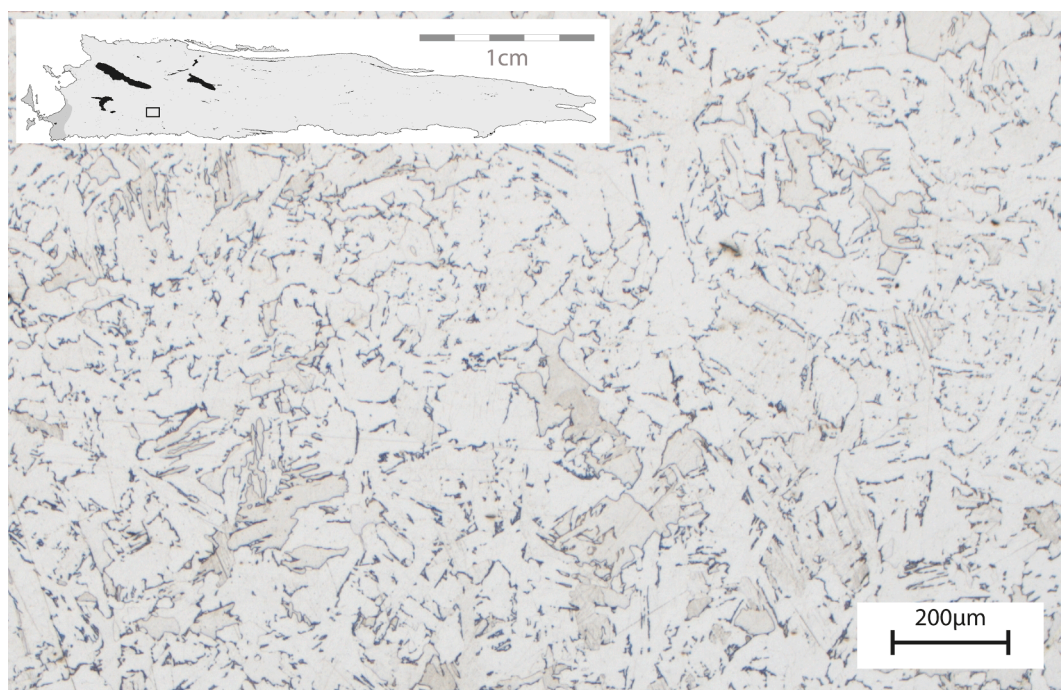


Fig. 13. Typical microstructure of OEG 968 sub 3.

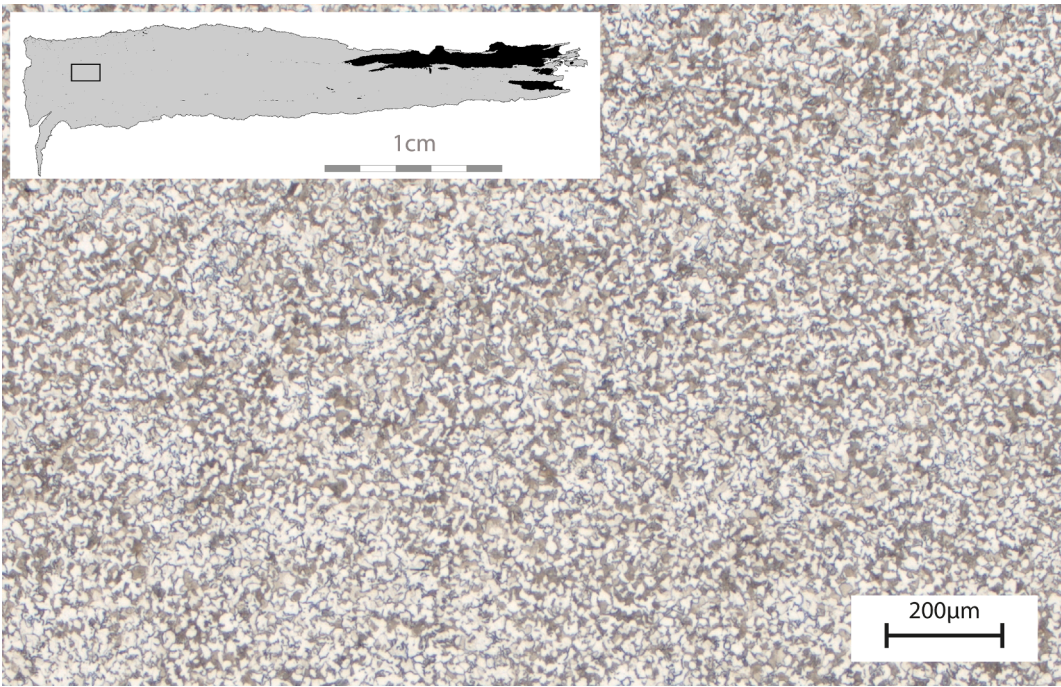


Fig. 14. Typical microstructure of OEG 2540.

Table 3
Synthesis of the results of the study of the slag from Oegstgeest.

Sample N°	Facies	Fayalite	Wüstite	Magnetite	Sediment	Charcoal inclusions	Corrosion product	Other
196 sub 3	SGD/SFR/SAS	x	x	possible	x			
226	SGD/SCD	x	x			x		
283A	SFR	x	x			x	x	
283B	SCD			x	x	x		Hercynite Yellow crystals Al rich needles Mg rich crystals S/Cu phases Cu prills
603	SFR	x	x		x	x	x	
662	SFR	x	x				x	
727	SAS	x	x		x	x		
2001 sub 2	SCD/SFR	x	x	x			x	
2001 sub 6	SAS	x	x		x			Fe prills
2011A	SFR	x	x				x	
2011B	SFR	x	x		x			Fe prills
2014	SFR	x	x		x		x	
2487	SCD	x	x			x		
2526	SFR	x	x				x	
3156A	SFR	x	x		x		x	Fe prills
5047	SGD/SAS	x	x					S rich surface deposit
5052	SGD/SAS	x	x					S rich surface deposit
5161	SFR	x	x			x		Fe prills
5763	Hearth lining				x			



Fig. 15. OEG 5355 etched with Nital.

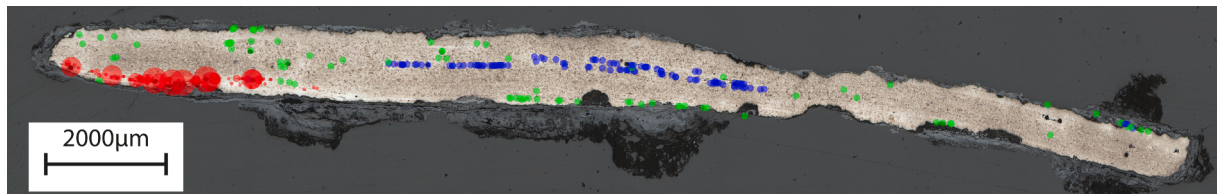


Fig. 16. Surface of OEG 968 sub 2 etched with Oberhoffer's reagent showing the group attribution of the slag inclusions by major element HCP.

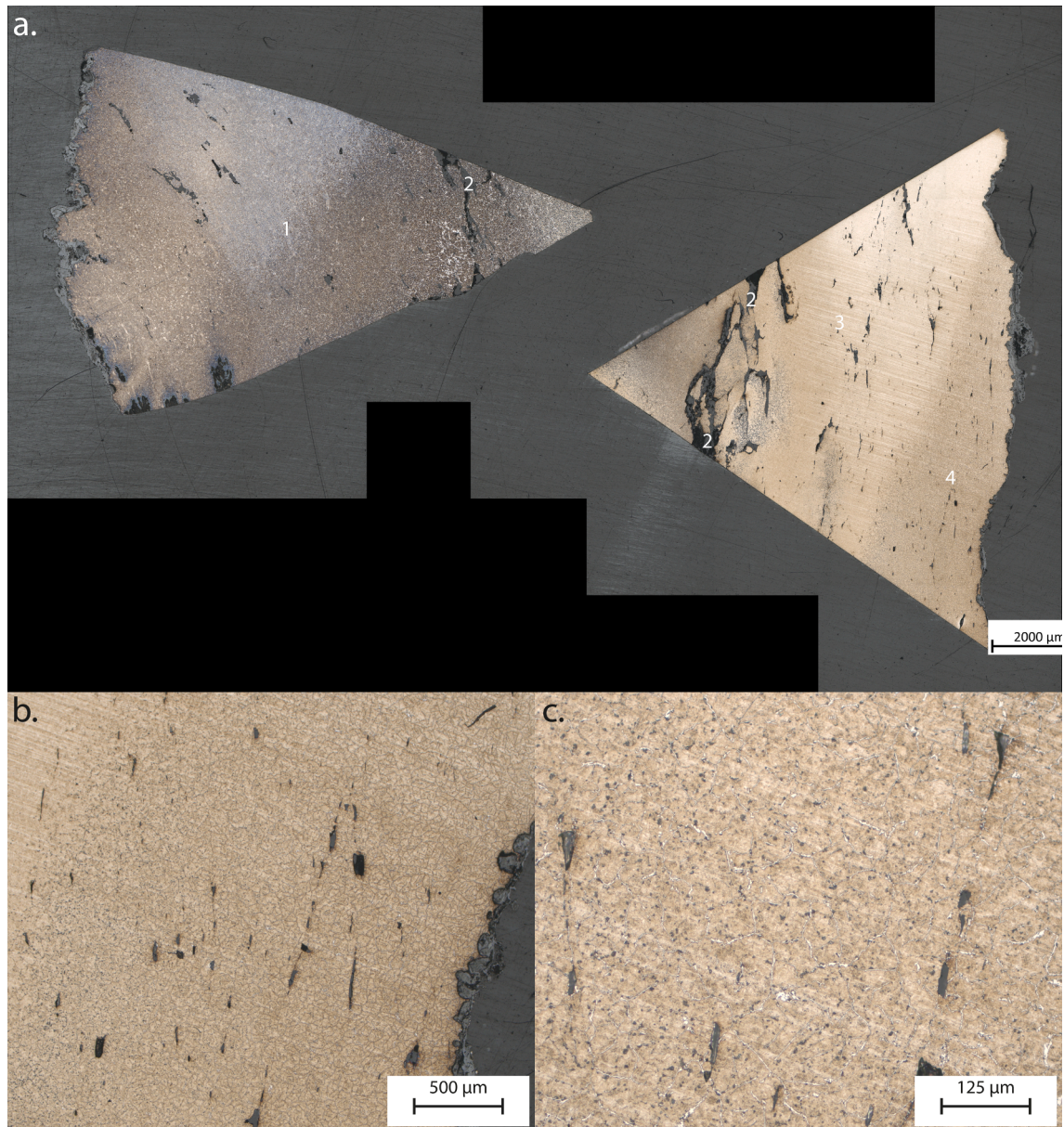


Fig. 17. OEG 968 sub 1. a. Overview of the sample surface etched with Nital, 1. Hyper-eutectoid steel, 2. slag inclusions in centre, 3. martensite, 4. martensite with cementite grain boundaries (displayed in Fig. 11b and c). b. Cementite grain boundaries surrounded by martensitic microstructure. c. Cementite grain boundaries at higher magnification.

site comparison, matched with samples from Bayerische Schwaben. However, the second round of HCPC attributed both of these sets of inclusions to groups containing only entries from the respective samples. The only firm attribution, in which the inclusions from the sample were indistinguishable with the entries of ore and slag, was OEG 968 sub 1 (fire striker) (see Fig. 22). Initial HCPC comparison against the full range

of candidate provenance spaces grouped the sample with entries from Swabia, Barrois, Minette and Fer Fort. A second HCPC was undertaken with these entries which grouped OEG 968 sub 1 with entries from Fer Fort. Subsequent HCPC was unable to distinguish between these entries, suggesting a common origin.

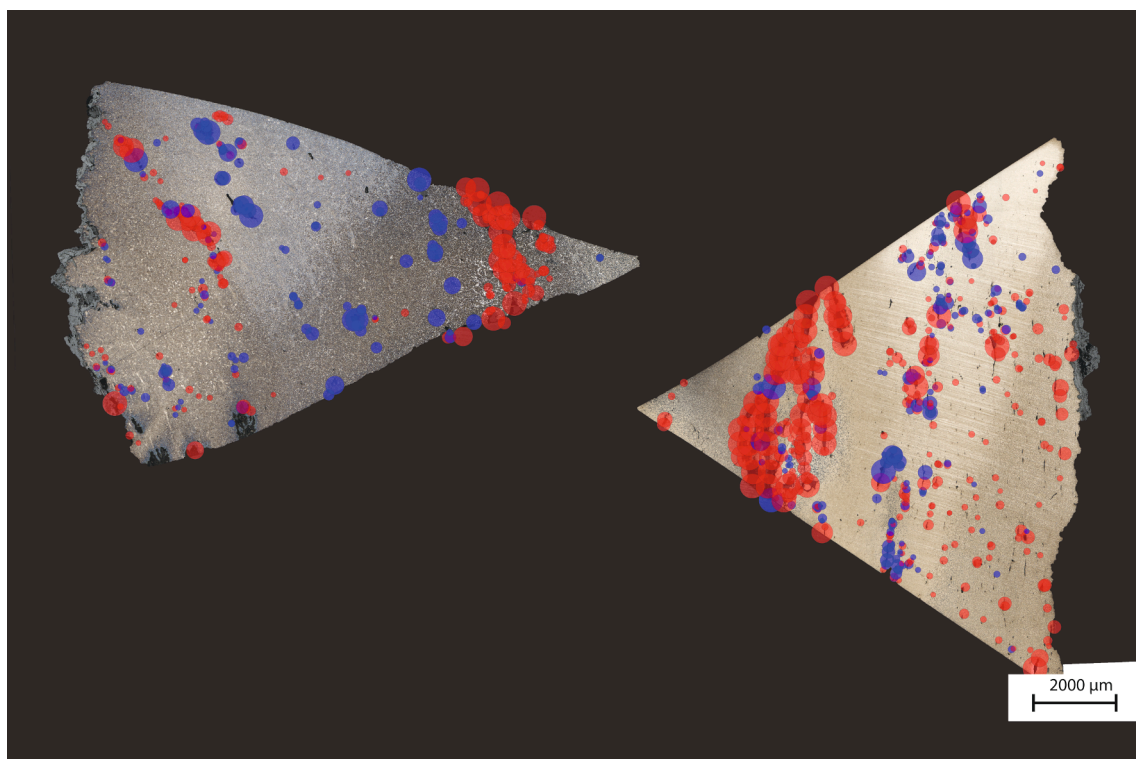


Fig. 18. Class attribution by major element HCP of the slag inclusions in OEG 968 sub 1.

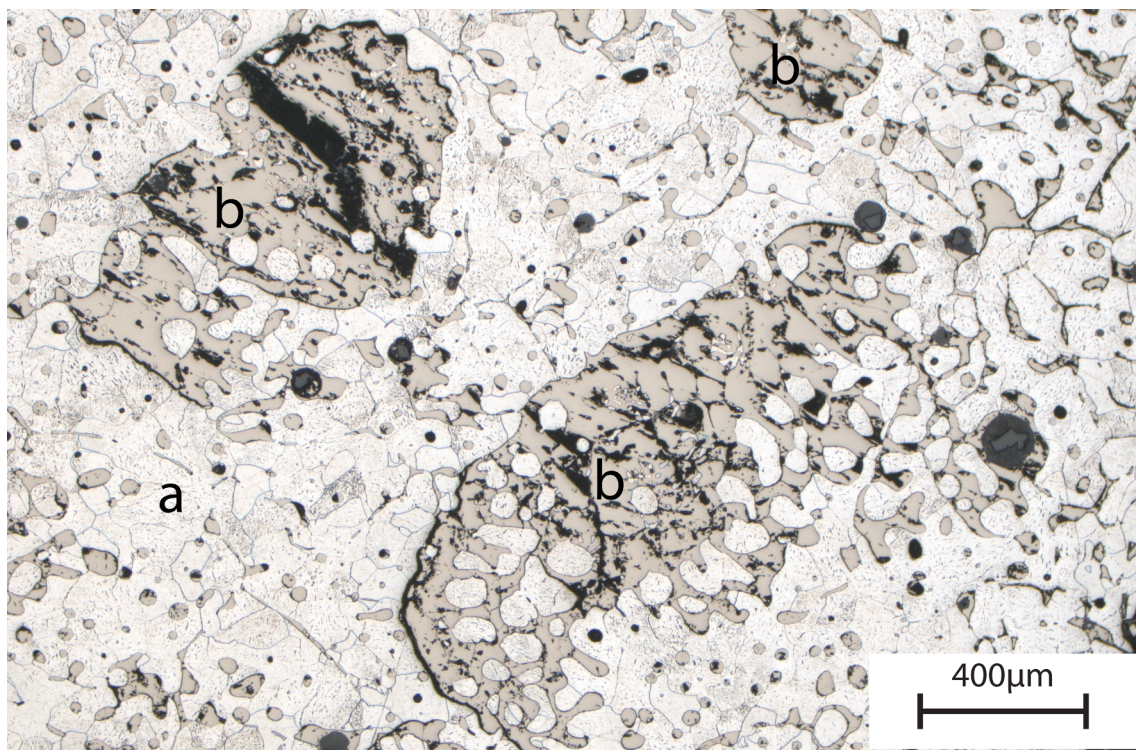


Fig. 19. Beige inclusions in OEG 180A. a. Iron matrix b. Sulphide inclusions.

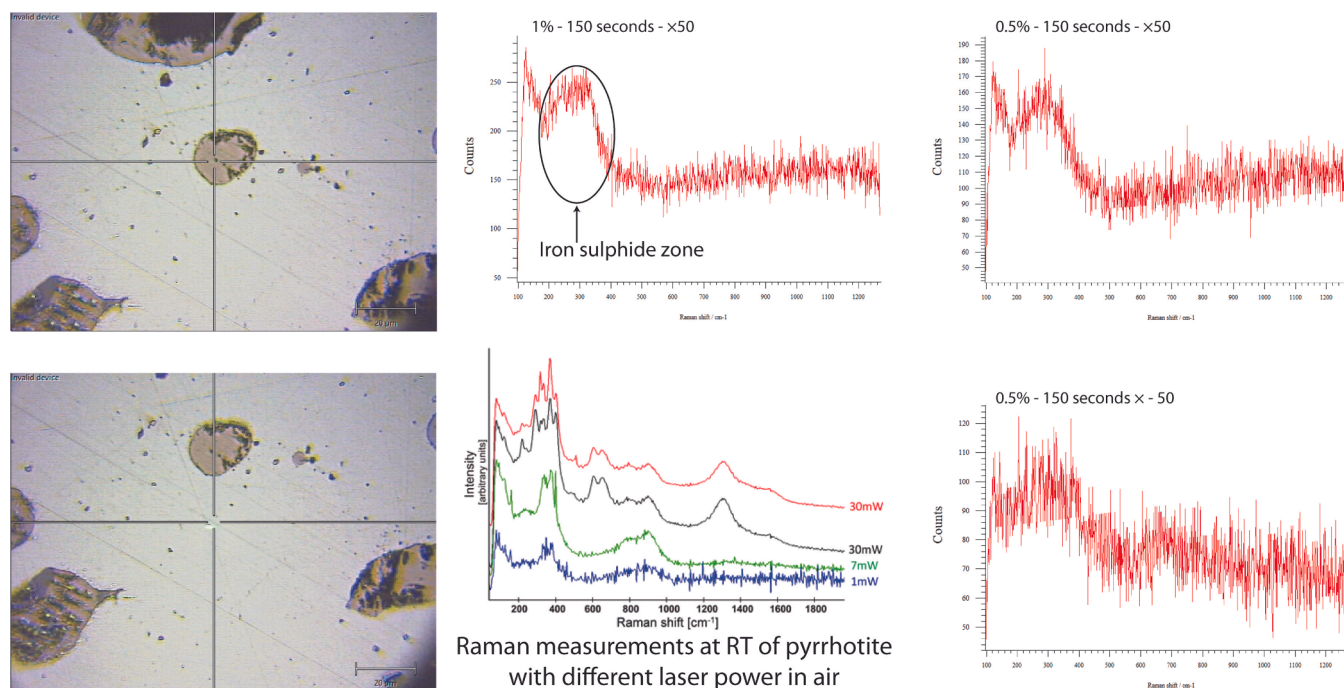


Fig. 20. Results of Raman Spectroscopy performed on the sulphide inclusions in OEG 180B.

4. Discussion

4.1. Iron working at Oegstgeest

Given the predominance of SAS and SFR forge slag, combined with the presence of forge scraps and finished objects, the results of this study complement [Disser's \(2019\)](#) conclusion that object creation and upkeep of objects was the primary form of iron working at Oegstgeest.

The metallurgical study revealed advanced techniques such as welding and quenching without any indications of poor execution (peripheral oxidation, trapped corrosion product or splitting along the weld line). Furthermore, OEG 5355 is a direct weld between iron and steel; these metals weld at different temperatures and maintaining both pieces at the correct heat while undertaking the weld would have required considerable experience ([Fluzin 2002](#)). This could indicate that the artisans at Oegstgeest were sufficiently experienced to undertake these operations, though it is difficult to confirm whether this would have taken place at the settlement. It is possible that finds such as OEG 968 sub 1 (fire striker), could have been imported to Oegstgeest as finished objects. This possibility seems all the more plausible given the extensive pre-existing evidence for trade and importation of finished goods at Oegstgeest. In contrast, it seems less likely that pieces of forge scrap like OEG 5355 were imported, as such finds are typically associated with iron working in their immediate vicinity. Furthermore, the presence of SAS slags, such as OEG 2001 sub 1 do indicate that such high temperature activities did take place on site.

The metallurgical study revealed another interesting aspect of the iron at Oegstgeest, namely the use of homogeneous steel, often with high carbon content. The steel used in OEG 968 sub 1 (fire striker), 968 sub 2 (possible knife fragment) and 5355 (iron bar) was eutectoid to hyper-eutectoid. Examples of such high carbon steel in the ancient world do exist ([Godfrey & van Nie 2004](#)) but these tend to be relatively rare, or attributed to specific kinds of objects. For instance, the presence of homogeneous high carbon steel in OEG 968 sub 1 (fire striker) was predictable, as similar microstructures have been previously observed ([Terekhova & Zavyalov 2019](#)). The use of such homogeneous steel in OEG 968 sub 2 and 5355, as well as in lower carbon pieces such as OEG 968 sub 3 and 2540 was not expected. Its presence on site could indicate

that metal of this quality was sufficiently available at Oegstgeest to be used in objects as common as nails. Some of these quality objects, based on the presence of steel in OEG 5355, may have been made on site.

4.2. High copper and sulphur content

4.2.1. Copper content

The copper prills observed in the hearth bottom OEG 603 are broadly similar with examples noted in the literature ([Eliyahu-Behar et al., 2012](#); [Vodyasov et al., 2021](#)). However, the examples in these studies were metallic copper rather than oxides and were an order of magnitude smaller (10–100 μm as opposed to ~1 mm diameter prills observed in OEG 603). Whether these prills were already corroded upon entry to the slag or whether they oxidised during sample preparation is difficult to establish. However, given that one of these prills is surrounded by a second (see [Fig. 6b](#)), and that they both present the same surface enrichment, it seems likely that these formed sequentially as liquid copper. The smaller metallic copper prills found at the surface of the slag are consistent with those described in the literature. It is possible that this surface sediment was formed in part by the remains of the hearth lining. In this case, copper would have been present in the hearth lining to find itself attached to the resulting slag.

There are three plausible origins for this copper. The first is brazing, in which copper would have been used to attach two pieces of iron, and could have resulted in a portion dripping into the hearth. The second possibility is that multi-metal objects were worked in this hearth. The final possibility is working iron and copper objects in tandem in the same hearth. This interpretation seems the most plausible given the clear evidence for copper recycling at Oegstgeest ([Theuws et al., 2021b](#)). In this scenario, a spill would have led to the presence of metallic copper in the hearth, which would have then been incorporated into the forge slag. One of the main questions surrounding polymetallurgy at Oegstgeest was whether iron and copper were worked during the same phase of occupation. If the presence of these prills is indeed an indication that iron and copper were worked in tandem, this not only confirms that the metals were worked during the same phase of occupation, but potentially even the same day. Furthermore, it implies that Oegstgeest had sufficient resources either to maintain two artisans working in parallel,

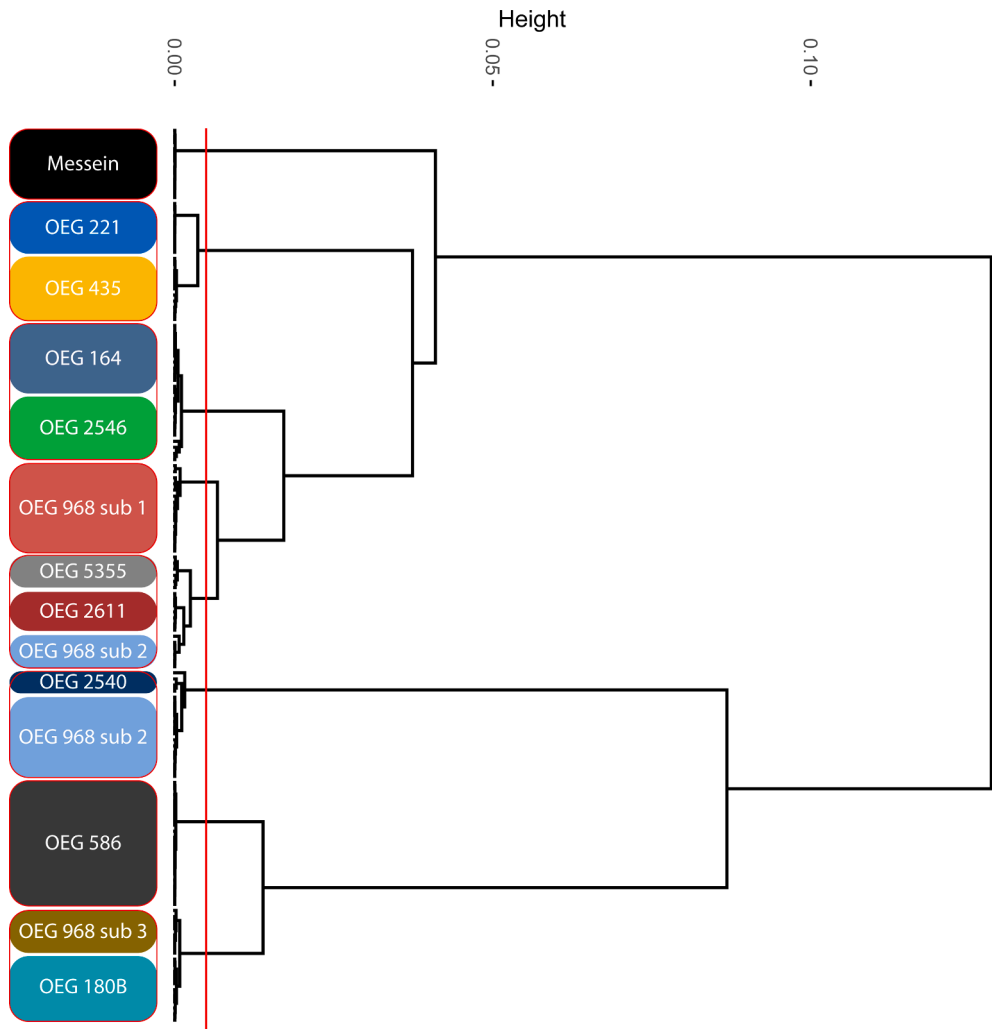


Fig. 21. Dendrogram resulting from the intra-site trace element HPCP.

Table 4
Synthesis of the results of the study of the iron from Oegstgeest.

Sample N°	Category	Microstructure	Other microstructure	inclusion % (proportion of surface)	Phosphoric ghost structures	Comments
164	Boat nail	Ferrite/hypo-eutectoid steel		3.0 %	No	
180A	Uncertain	Ferrite	Poorly formed grain and few slag inclusions	29.8 %	No	S rich inclusions disaggregating into iron matrix
180B	Nail	Ferrite		4.1 %	Yes	Cu in slag inclusions
221	Boat nail	Ferrite		2.8 %	Yes	Possibly modern
435	Nail	Ferrite	Twinning in grain	7.6 %	Yes	
586	Forge scrap	Ferrite		3.6 %	No	
968 sub 1	Fire striker	Eutectoid/Hyper-eutectoid steel	Martensite	5.4 %	No	
968 sub 2	Knife fragment?	Eutectoid steel	Steel/Steel weld	0.5 %	No	
968 sub 3	Nail	Hypo-eutectoid steel	Homogeneous acicular grain	2.6 %	Yes	
2540	Nail	Hypo-eutectoid steel	Homogeneous round small grain	9.5 %	No	Cu in slag inclusions
2546	Nail	Ferrite	Twinning in grain	2.6 %	Yes	
2611	Nail	Ferrite/hypo-eutectoid steel	Iron/Steel weld	4.0 %	Yes	
5355	Forge scrap	Ferrite/hypo-eutectoid steel	Iron/Steel weld	2.3 %	Yes	

Table 5
Synthesis of the provenance study.

Sample	Category	Intra-site match	Provenance attribution	Comments
164	Boat nail	2546	None	
180A	Uncertain	N.A.	None	Too much internal variation to be included in intra site comparison
180B	Nail	968 sub 3	None	
221	Boat nail	435	Bayerische Schwaben?	Some chemical variation, 2 inclusions in separate branches of the provenance dendrogram than the rest
435	Nail	221	Bayerische Schwaben?	
586	Forge scrap	None	None	No match with any of the included sources
968 sub 1	Fire striker	None	Fer Fort	.
968 sub 2.1	Uncertain, possibly knife blade	5355 & 2611	N.A.	Likely forge inclusions
968 sub 2.2	Uncertain, possibly knife blade	2540	None	
968 sub 3	Nail	180B	None	Outliers with Schwäbische Alb
2540	Nail	968 sub 2.2	None	
2546	Nail	164	None	
2611	Nail	968 sub 2.1 & 5355	N.A.	Likely forge inclusions
5355	Small bar	968 sub 2.1 & 2611	N.A.	Likely forge inclusions

or that at least one smith had experience with both metals.

It is tempting to link the copper observed in OEG 180B and 2540 (nails) with this polymetallurgy and attempts at brazing iron using copper as a filler could theoretically result in copper being present in some of the forge inclusions. Confirming or refuting this hypothesis would require further study. If brazing was not taking place, it is highly unlikely that this copper is of the same origin as that noted in OEG 603. Any copper in the smelting inclusions could only have entered the metal during the smelting process and are unlikely to have contributed to the copper in this sample. While a small portion of such slag inclusions could have entered the hearth due to the forging of samples like OEG 180B and 2540, this would be a negligible contribution to slag composition when compared with the forge scale, hearth lining and fuel.

4.2.2. Sulphur content

Despite the differing stoichiometric ratios of iron and sulphur between these samples, the presence of the iron sulphide deposit in OEG 5047 and 5052 could be explained by the forging of samples which contained large numbers of iron sulphide inclusions, such as OEG 180A (Craddock & Lang 2005). However, as no other such samples were found at Oegstgeest, this remains speculative. Nevertheless, OEG 180A remains interesting as the sample most resembles a “gromp”, a small fragment of iron bloom. This could be taken, alongside the possible smelting slag found at Oegstgeest, as evidence of some smelting activities in the area. This too remains speculative as both finds are outliers and the lack of smelting structures precludes the possibility of smelting within the settlement itself. Nevertheless, OEG 180A does raise the question of the origin of these sulphide inclusions.

High sulphur concentration in iron is typically provided by the ore (Craddock & Lang 2005) but some sulphur rich fuel sources can produce

iron sulphides, specifically coal. Within the Netherlands, coal use is documented during the Roman period with evidence of smithing slags containing coal in the settlements of Vechten and Kesteren (Joosten 2004). Coal use decreased in the Early Middle Ages, a trend noted across Western Europe at this time (Jagou 2020) but it is possible that small-scale coal use continued into the Merovingian period. However, coal use is typically limited to forge activities and the shape and distribution of these inclusions indicate that they originated during the smelt. Furthermore, none of the forge slags from Oegstgeest match the typical facies of coal forge slags, i.e. no coal or jarosite inclusions and relatively dense morphology (Jagou 2019). This does not completely rule out the possibility of sulphur contamination from the fuel as Stepanov et al. (2022) found that sulphur contamination of wood charcoal can lead to the formation of pyrrhotite inclusions in the iron bloom. A final possibility for sulphur from the fuel would be the use of peat. Given its prevalence in the Netherlands, it is theoretically possible that peat could have been used as a fuel source, though its relatively low calorific value, 20–25 MJ·kg⁻¹ as opposed to ~30 MJ·kg⁻¹ for charcoal (Johansson et al. 1986), would make this a poor choice of fuel. Furthermore, due to the extended contact between the fuel and the slag, it is likely that this would result in a portion of the peat being trapped as inclusions and cause an increase of K and Al content in the slag, as is seen with coal. None of these were noted at Oegstgeest, meaning that the use of peat is also unlikely.

This leaves the ore as a possible source of sulphur, which raises several questions. Stepanov et al. (2022) also found that despite a beneficiation regiment (roasting, hydro panning and sorting), it is possible for sulphur rich ores to retain a significant portion of the sulphur during the smelt. Tumiati et al. (2005) studied a collection of 9th century slags produced using Servette-Chuc ore, a Pyrite (FeS₂) rich ore with occasional “flames” of chalcopyrite (CuFeS₂) from the Val d'Aosta in Northern Italy. Rather than spreading evenly throughout the bloom, sulphur was found as troilite (FeS) inclusions caught within the iron matrix. This raises some possibilities as to the origin of OEG 180A: most Dutch ores are found in sedimentary contexts (Joosten 2004) which can result in some pyrite deposits. However, the use of ore containing chalcopyrite could potentially explain the copper observed in the slag inclusions of OEG 180B and 2540 (nails). If this is the case, this would require a volcanic origin, placing the closest possible source of ore in the Eifel. As previously noted, OEG 180A is a unique sample at Oegstgeest but it would be of interest to compare the sample with iron known to be smelted with sulphur rich ores from this region.

4.3. Provenance and sources of iron

Despite only being able to establish a firm link between one sample (OEG 968 sub 1, fire striker) and one candidate provenance space (Fer Fort), the intra-site comparison established 6 distinct groups chemical groups of slag inclusions amongst the iron objects at Oegstgeest. This would suggest that as many sources of iron were used at the settlement. As previously mentioned, the wider Netherlands, specifically the Veluwe, is a good candidate for any iron worked at Oegstgeest. Should compatible data for this provenance space be published, it is likely that at least one of the objects from Oegstgeest will match with it.

It is possible that different sources from the Netherlands could account for the full range of chemical variation seen at Oegstgeest. However, given the evidence for medium to long distance trade already established at the settlement (Kars et al., 2018; Theuvs et al., 2021a) it would be a mistake to neglect sources of iron from further afield. With this in mind, two regions stand out:

The presence of English artefacts at Oegstgeest suggests contact with the British Isles. Cross-North Sea trade is well documented at this period (Lovelluck & Tys 2006) and it is entirely possible that iron was traded alongside other goods. As of yet, English ores have not been as extensively studied as their continental counterparts and if and when compatible data becomes available, it would be interesting to compare it

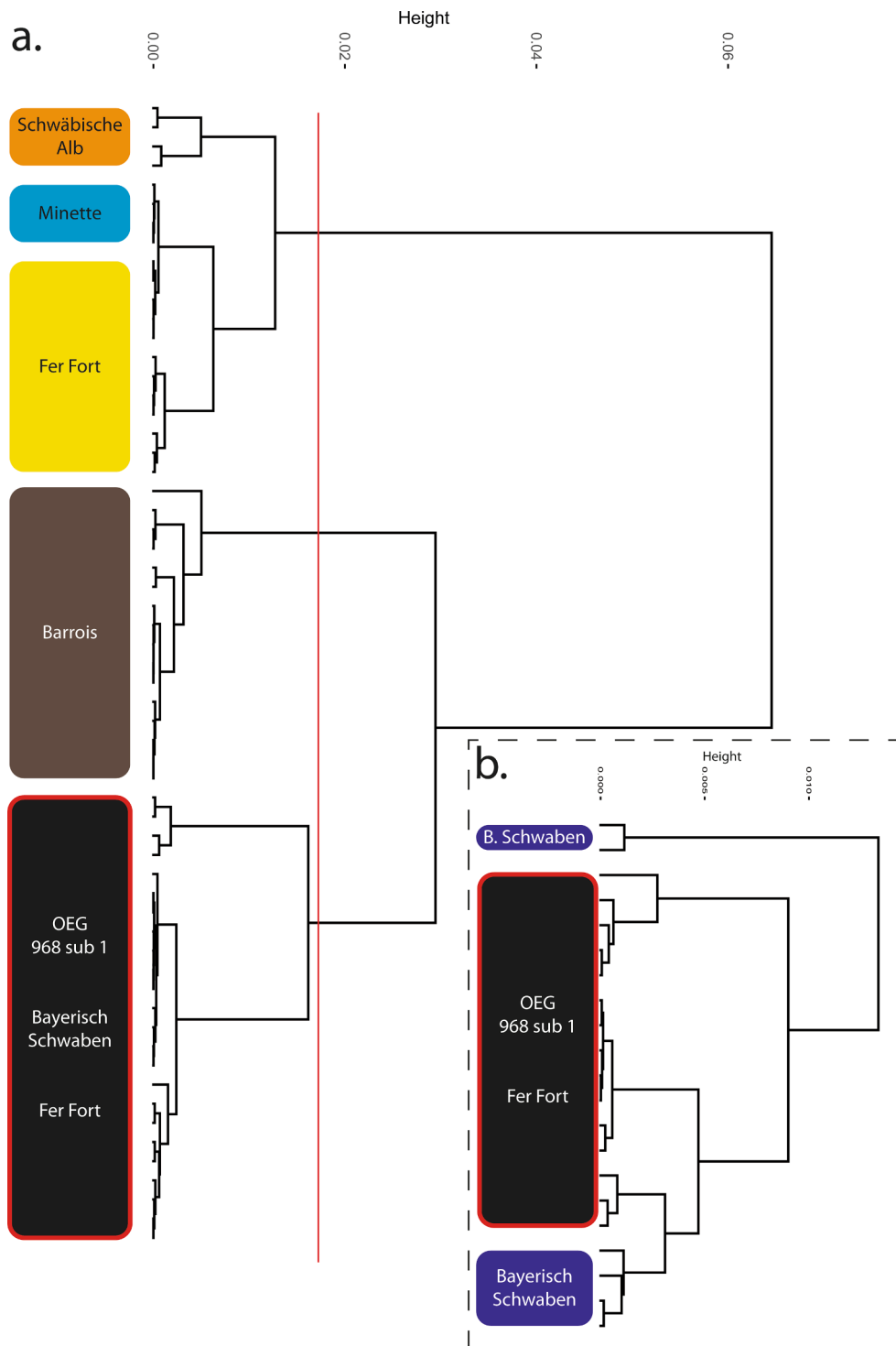


Fig. 22. HCPC analysis of trace elements in the inclusions from OEG 968 sub 1 (fire striker) compared with the candidate provenance spaces. The first round of comparison found possible matches with Swabia, Barrois, Minette and Fer Fort. a. The second round of HCPC refined the match with entries from Bayerische Swchaben and Fer Fort. b. The third round of HCPC found greater similarity with Fer Fort and subsequent analyses were unable to distinguish further between the inclusions from OEG 968 sub 1 and the Fer Fort entries.

with the finds from Oegstgeest.

Another conceivable source of iron is the Danube. During the Early Middle Ages, the Rhine and the Danube formed the main axis of communication between Eastern and Western Europe (van Es & Verwers 2010). Contact between Oegstgeest and the Mediterranean was already established prior to this study. For Mediterranean goods to reach the settlement, these would most likely have been traded up the Danube and

down the Rhine. It is possible that iron from along the Danube River, either as finished objects or semi-products, was one of the goods traded along this route. Data from these regions was considered as a possible source of iron from Oegstgeest but other than the entries from Swabia, Danubian data was not included in the provenance study for two reasons. Firstly, the distance of these sources relative to the others considered for this study and secondly the lack of extant data for much of

the region.

5. Conclusion

The study of both the slag and metal samples has built on the conclusions of Disser (2019) and has, in many respects surpassed them. As was previously established, secondary ironworking, specifically the creation and upkeep of finished objects took place at Oegstgeest. The presence of homogeneous steel, as well as complex objects like fire strikers, suggests that quality goods and materials were available to the inhabitants of the settlement. This is backed by the other imported goods found at Oegstgeest (Theuws et al., 2021a). Furthermore, the remains of iron working seen at Oegstgeest show a range of advanced techniques, from direct welding of iron and steel to differential quenching as well as likely tandem iron and copper working, though it is possible that some of the more complex finds were traded to the site from elsewhere as finished objects.

The presence of sulphur rich inclusions in OEG 180A remains confusing as it is unclear how they could have formed, though the possibility of coal use can be discarded. These inclusions could be the result of smelting pyrite rich ores, an explanation that could potentially explain the anomalous presence of copper in OEG 180B and 2540 but many questions persist. Further study will be required to understand these samples properly.

Chemical provenancing was inconclusive though intra-site comparison established several distinct groups of trace element chemistry, suggesting the use of a variety of sources of iron at Oegstgeest. One object was able to be reliably associated with Fer Fort iron from Lorraine while an additional two objects matched less reliably with Swabia in southern Germany. Should compatible data become available, the finds from Oegstgeest would benefit from a comparison with data from the Netherlands, England and the Danube.

In summary, the findings of this study indicate that the Merovingian settlement at Oegstgeest had access to quality materials, finely wrought finished objects and skilled artisanship. These compliment the overall study of the site (Kars et al., 2018; Theuws et al., 2021a) in suggesting that it was not merely a disconnected poor settlement. Instead, Oegstgeest had the skilled artistry, quality materials and the resources required to import and create valuable iron goods.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary materials

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2023.104236>.

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