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

4 Authors

5 Tobias Heal 1, 2, 3

6 Alexandre Disser 1, 2

7 Florence Mercier 1, 2

8 Guillaume Sarah 4

9 Frans Theuws 5

- 11 1. Laboratoire Archéomatériaux et Préviation de l'Altération, IRAMAT UMR7065, Université Paris-Saclay, CNRS, 91191, Gif-sur-Yvette Cedex, France
- 12 2. Laboratoire Archéomatériaux et Préviation de l'Altération, NIMBE UMR 3685, CEA, CNRS, Université Paris-Saclay, 91191, Gif-sur-Yvette Cedex, France
- 13 3. ULG, European Archaeometry Centre (CEA), University of Liège, 4000 Liège, Belgium
- 14 4. Institut de Recherches sur les Archéomatériaux – Centre Ernest Babelon, CNRS, Université d'Orléans, 3D rue de la Férollerie, 45071, Orléans Cedex 2, France
- 15 5. Faculty of Archaeology, Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands

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22 The Early Middle Ages were a time of major societal, political and economic upheaval in the Rhine
23 Delta. Though on the outskirts of the Roman world, the collapse of the Western Roman Empire led to
24 significant changes in the region's ethnic and cultural make-up (Wood 1994; van Es and Verwers
25 2010). These changes, combined with the lack of written sources, have led to this period being one of
26 the most poorly understood in Dutch history. Archaeological study has shed light on the daily realities
27 of this time, but many questions persist. In particular, the role of “marginal communities” (Loveluck and
28 Tys 2006) remains unclear. Many studies have stressed the role played by secular and religious elites
29 in overseeing the economy of the Early Middle Ages (Pirenne 1937; Besteman et al. 1990) but the
30 study of rural settlements has revealed considerable prosperity outside of such power structures
31 (Henning 2007). Merovingian Oegstgeest is an example of such a settlement. At first glance, the site
32 appears to be an isolated backwater but the finds paint a more nuanced picture.

33 An in depth overview of the site has already been undertaken by Bruin et al. (2021). Rather than
34 re-iterate the results of this work, this paper approaches the settlement through the remains of a
35 specific material: iron. Clear evidence of ironworking was found at Oegstgeest, including iron slag,
36 metallic forge scrap and finished objects. The study of this material can provide considerable insight
37 into the socio-economic role of the settlement and shine light on the realities of forging in the Early
38 Medieval Rhine Delta.

39 *Iron in the Early Medieval Netherlands*

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

1 The Netherlands is not known for its mineral resources but there is clear evidence of Early
2 Medieval iron production in the region (Joosten 2004). Many Dutch smelting sites relied on bog iron
3 ore, accumulations of iron rich minerals precipitated in sandy, silty or clayey sediments (Thelemann et
4 al. 2016) but there is also evidence for the use of other kinds of mineral deposits. This is especially
5 true in the Central and Eastern Netherlands with the most prominent Early Medieval example being
6 the Veluwe (Gelderland). Wide spread iron smelting in this area (with more than 70 slag heaps
7 identified) became a phenomenon as early as the 7th century and this continued until the mid-9th
8 century (Joosten 2004). in the region, as well of open cast mining pits and deposits of rattle stone ore
9 in certain strata. Alongside these local sources, it is equally plausible that smiths in the Early Medieval
10 Netherlands were using iron from further afield. Bruin et al. (2021) found extensive evidence for
11 medium to long distance trade at Oegstgeest both along the Rhine and Meuse Rivers, and across the
12 North Sea, complementing similar evidence in other Dutch sites from this time (Loveluck and Tys
13 2006; Deckers and Tys 2012).

14 There has been very little study of smithing activities in the Early Medieval Netherlands. What
15 studies exist typically focus on the typology and microstructure of individual finds rather than wider
16 questions of production. Furthermore, centres of trade and power such as Dorestad and Nijmegen
17 typically take centre stage with rural contexts being ignored (c.f. Ellis 2002; Willemsen et al. 2021).
18 Worked iron has been identified and characterised at some smelting sites; such as Heeten in
19 Overijssel (Godfrey and van Nie 2004) but these again focus on individual finds. Joosten (2004) also
20 documented some possible smithing slags from the Veluwe but these were not characterised further. It
21 is for this reason that the study of a rural site like Oegstgeest is of such interest, as it offers a window
22 into two understudied contexts.

23 ██████████ *Merovingian Oegstgeest*

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

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

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

1 Theuws et al. posit that there may have been 60 people living at Oegstgeest at any moment of its
2 existence.

3 Despite the settlement's proximity to the coast, Oegstgeest was primarily a riverine site. At the
4 time, the Oude Rijn was one of the largest distributaries of the Rhine Delta and this had a major effect
5 on the character of the settlement. Oegstgeest appears to have been a logical stopping point between
6 the North Sea and the lands upriver (Theuws et al. 2021a), a connection reinforced by the large
7 number of imports identified during excavation. These include simple finds, such as wooden bowls and
8 everyday utensils but also more complex objects. For example, 122 glass shards were recovered from
9 the settlement, the majority of which came from vessels or other containers (Van Wersch 2021).
10 These were typologically consistent with vessels dating to the 6th and 7th centuries, suggesting that
11 glass was imported during the entire occupation of the site. Other finds included glass beads; some
12 produced locally, some from as far as the Mediterranean, worked amber from the Baltic, as well as
13 several exceptional finds, including a silver bowl from the Mediterranean. Theuws et al. (2021a) also
14 found evidence of imported foodstuffs. Several wooden barrels were found to have contained wine,
15 likely from the middle Rhine and further study confirmed the presence of grain, rye, grapes, figs and
16 possibly walnuts, none of which are likely to have grown in the region. Evidence of cross North Sea
17 trade was also present, visible through 24 silver *sceattas*, mostly of the D and E series, a type found in
18 both England and the Netherlands. In addition, an English style horse bit was uncovered, though it is
19 unclear whether this was imported from England or made locally in English style.

20 There was also clear evidence of local production. Three soled leather shoes, a rarity at this
21 period, were found at Oegstgeest alongside the materials and tools required to make them (Theuws et
22 al. 2021a). Additional evidence for local production included metalworking; 3 gold ornaments and over
23 200 finds related to copper working were uncovered. Most of these were brooches though several
24 crucible fragments were also found, one of which was attached to a copper alloy fragment. These
25 metal finds were fragmented and seem to have been in the process of being recycled (Theuws et al.
26 2021b). Furthermore, there was extensive evidence for iron working at Oegstgeest.

27 As of yet, no forge or metal workshop has been identified at Oegstgeest but the evidence for iron
28 working is indisputable. Over 43 kg of iron slag was recovered alongside 2.4 kg of metallic finds (see
29 figure []). The findings of the preliminary study of this material is synthesised here (Disser 2019;
30 Theuws et al. 2021b).

31 Slag finds

32 Disser (2019) established that that 17 kg of the slag from Oegstgeest, about 40% of the corpus,
33 was smithing slag, with the remaining slag being mostly amorphous (see figure []). Three quarters of
34 the smithing slag recovered from Oegstgeest weighed less than 300 g though 39 larger hearth
35 bottoms were uncovered. In addition, a very small quantity of slag (303 g) was identified by Disser as
36 possible tap slag but this was determined to be too small to ascertain that smelting was taking place
37 on site. Of the hearth bottoms, 15 were plano-convex, 4 were biconvex, 4 were faceted, 3 were planar,
38 2 were concave and 1 was conical. The remaining hearth bottoms were irregular shapes. Average
39 slag length and width were 93 and 70 mm respectively and average thickness was 45mm.

40 Macroscopic petrographic study established that SGD (*Scorie Grise Dense*, dense grey slag) was
41 the most represented facies in the corpus, with 51% of the slags containing at least some SGD (see
42 Serneels 1993; Anderson et al. 2003; Serneels and Perret 2003; Eschenlohr et al. 2007 for details on
43 slag facies). However, 33% of the slags also contained SFR (*Scorie Ferreuse Rouillée*, rusty ferric
44 slag) with this facies being dominant in 21%. SAS (*Scorie Argilo-Sableuse*, clay and sand slag) was
45 present in 36% of the corpus but was only the dominant facies in 10 hearth bottoms (25% of the
46 corpus) (see figure []). In addition, Disser identified a potential fourth facies, which he dubbed SCD
47 (*Scorie Crystalline Dense*, dense crystalline slag) in 13% of the corpus. This facies is superficially
48 similar to SGD though the hearth bottoms had flat, well-preserved sides, which Disser associated with
49 the possible presence of macro-crystals.

50 Finally, Disser (2019) used this information to quantify smithing activities at Oegstgeest. As no
51 dedicated forge was identified, Disser was unable to establish the quantity of iron waste in the relevant

1 contexts and instead based his reasoning on the slag and other scoriaceous waste found on site.
2 From this, he found a loss between 9.5 and 12 kg of iron during forging. With careful comparison with
3 similar sites in the literature (Mangin et al. 2000; Perret 2002) he gives a cautious estimate of 90 to
4 432 kg of iron objects produced over the lifetime of the site.

5 ██████████ *Iron finds*

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

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

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

21 To reach these goals, this paper sets the following objectives. Firstly, to establish the forge techniques
22 used at Oegstgeest. Secondly, to establish the provenance of the iron used at Oegstgeest and finally,
23 to consider the implications of these results on the nature of iron working at Oegstgeest. This will
24 consider these can reveal about the role of the settlement as a place of iron production in the Early
25 Medieval Netherlands and also what they imply for the role of the settlement within its wider context.

26 Of the remains of metalworking at Oegstgeest, 36 finds were selected for this study (see Table []
27 and figure []). Among the slag, 15 hearth bottoms were chosen, including at least one instance of each
28 of the four facies identified by Disser (2019). Additional hearth bottoms were chosen to reflect the
29 distribution of facies at Oegstgeest with complete hearth bottoms being privileged. This was
30 complemented by three pieces of amorphous slag, one of which was found in the same context as one
31 of the hearth bottoms. The remaining two were selected in the hopes of characterising an unidentified
32 surface deposit. Due to the generally poor condition of the metal finds from Oegstgeest, iron samples
33 were selected on two criteria: that they had not already been selected for museum display and their
34 likelihood of containing metallic iron. No X-ray imagery was performed and this was instead
35 established by magnet response and apparent density. Thirteen iron finds were chosen for the final
36 corpus: 8 nails, including 2 boat nails, 2 pieces of forge scrap to characterise the smithing activities, 2
37 complex objects in the hopes that these might reveal some more advanced forge processes that may
38 have taken place on site and 1 unidentified sample.

39 Sample preparation was based on similar studies (Pagès 2011; Disser et al. 2016; Berranger et al.
40 2017; Disser et al. 2020). The slag samples were cut using a Struers Unitom-2 circular saw. The iron
41 samples were cut using a Struers Accutom-50 saw along their length to provide an overview of the
42 piece. Two larger samples (OEG 164 and 221, boat nails) had approximately 1.5 cm cut from the
43 end, which was then cut in half. OEG 968 sub 1 (fire striker) had two triangular sections removed at
44 different heights to examine the full width of the piece while preserving its structural integrity. Once cut,
45 the larger samples were embedded in Struers EpoFix epoxy resin and smaller samples (>2cm in
46 length) were embedded in transparent acrylic under pressure for five minutes using a Metkon
47 Ecopress 52. The resulting samples were polished using abrasive disks and diamond solution (grade
48 P80 paper to 1µm diamond solution) to obtain a mirror finish.

49 ██████████ *Optical microscopy*

1 Metal samples were etched first using Nital (4 vol% HNO₃ in ethanol) then polished and etched
2 again using Oberhoffer's reagent. In both cases, the surface was studied by reflected light microscopy
3 using a Zeiss Axio Imager A2 Vario. Low magnification micrographs were taken across the surface of
4 the sample using a Zeiss Axiocam camera. These were assembled to create a mosaic image of the
5 surface microstructure using Zen Core v. 3.3. Areas typical of the microstructure of the sample, as well
6 as any areas of metallurgical interest were photographed. The proportion of pearlite was used to
7 establish the approximate carbon content of each sample (c.f. Pagès 2011; Gosselin 2021). Slag
8 samples were analysed and photographed using the same setup to establish mineral compounds
9 present within the slags.

10 SEM-EDX

11 A 20 nm carbon coat was applied to the samples using an Agar Auto Carbon Coater, which were
12 then subjected to elemental analysis by energy dispersive X-ray spectrometry coupled with scanning
13 electron microscopy. This was accomplished using a JEOL SEM-FEG 7001 equipped with a silicon-
14 drift detector. Accelerating voltage was set at 15 kV, working distance at 10 mm and probe current
15 around 8 nA. This allows for reliable quantification of elements over 0.3-0.5 wt%, depending on the
16 element in question. An automated filter was applied to each spectrum to remove the background
17 contribution. Quantification of chemical elements was processed using XPP matrix correction routine
18 (with a Phi-Rho-Z function). O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe and Cu were
19 systematically quantified, and results were normalised to 100%. The iron samples were studied using
20 the same protocol as Disser et al. (2020): slag inclusions in the iron matrix were systematically
21 analysed by backscattered-electron imagery using x300 magnification. This process generated a
22 spreadsheet detailing spatial (location, size, and shape) and chemical data for each identified particle.
23 This was used to compliment the metallurgical study by as it allows the differentiation of forge and slag
24 inclusions, as well as identifying areas made from separate blooms (c.f. Disser et al. 2020).

25 Slag samples containing a microstructure seen in all or most of the respective slag facies (SGD,
26 SAS, SFR and SCD) were also analysed by SEM-EDX (see Table []). Additional SEM-EDX analysis
27 was performed on slag samples containing phases that were unable to be identified by optical
28 microscopy. A 2 cm² sample of the area of interest was identified using optical microscopy and
29 sampled using a Brot geological saw. These were then re-embedded in Struers EpoFix resin, carbon
30 coated and analysed using the pre-established parameters combined with the cartography tool in
31 Aztec. The results of these findings are summarised in table [] and table [] for iron and slag
32 respectively. Full results are available in the supplementary material.

33 LA-ICP-MS

34 Establishing possible origins for the iron used at Oegstgeest was based on trace element content
35 in slag inclusions. This was quantified by Laser Ablation Inductively Coupled Plasma Mass
36 Spectrometry at the IRAMAT Centre Ernest Babelon in Orléans. Set up and methodology was
37 modelled on that used by Bérard et al. (2020), itself based on the protocol detailed in L'Héritier et al.
38 (2016). Measurements were performed using a sector field Thermo Scientific ICP-MS Element XR
39 coupled with an ArF* excimer laser ($\lambda=193$ nm, RESOLUTION S155-E, Resonetics). Beam diameter was
40 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
41 pulse. The ablated particles were carried to the plasma torch using an Ar/He carrier gas (1.01 L·min⁻¹)
42 which was used to form the plasma. Cooling gas flow rate was 16 L·min⁻¹ with an auxiliary gas flow
43 rate of 1 L·min⁻¹. Measured isotopes were: ⁹Be, ²⁸Si, ⁴⁷Ti, ⁵¹V, ⁶⁰Ni, ⁶³Cu, ⁶⁹Ga, ⁷²Ge, ⁷⁵As, ⁸⁵Rb, ⁸⁸Sr,
44 ⁸⁹Y, ⁹⁰Zr, ⁹³Nb, ¹¹⁸Sn, ¹³³Cs, ¹⁷⁸Ba, ¹³⁹La, ¹⁴⁰Ce, ¹⁴¹Pr, ¹⁴⁶Nd, ¹⁴⁷Sm, ¹⁵³Eu, ¹⁵⁷Gd, ¹⁵⁹Tb, ¹⁶¹Dy, ¹⁶⁵Ho,
45 ¹⁶⁷Er, ¹⁶⁹Tm, ¹⁷²Yb, ¹⁷⁵Lu, ¹⁷⁸Hf, ¹⁸¹Ta, ¹⁸²W, ²⁰⁸Pb, ²³²Th and ²³⁸U. Time per sample was 10 ms with
46 100 samples per peak. Due to the varying size of slag inclusions, the quantity of ablated material was
47 a function of inclusion size so the net-recorded signal for each trace element was normalised using
48 ²⁸Si as an internal standard. This was measured using Faraday detection mode with a segment
49 duration of 100 ms. All other isotopes were measured using triple detection mode with a segment
50 duration of 40 ms.

51 The samples were placed in ablation cells alongside a NIST610 standard reference glass for
52 calibration. Bérard et al. (2020) found this to be the closest approximation to slag inclusions. At the

1 start of each session, a blank signal was obtained for 20 s to measure the background noise. The
2 NIST610 was then measured 3 times followed by 18 measurements of the archaeological samples,
3 after which this process was repeated. Once all samples were analysed, a final blank and 3
4 measurements were performed on the NIST610. In total, 12 slag inclusions per sample were selected
5 for analysis. The goal was to choose inclusions representative of the sample as a whole so the choice
6 of slag inclusions was informed by the results of SEM-EDX analysis: for samples made from multiple
7 blooms, an equal number of inclusions were chosen on both sides of the weld line. Large slag
8 inclusions were preferred to limit accidental ablations of the metal matrix.

9 ██████████ Raman spectrometry

10 The study of OEG 180A revealed inclusions that were unable to be fully characterised by optical
11 microscopy or SEM-EDX analysis. These were further studied using Raman spectrometry to establish
12 the precise mineral compound. This was accomplished using a Renishaw Invia Reflex spectrometer
13 equipped with a doubled Nd-YAG laser ($\lambda=532$ nm) and a Leica DMLM microscope using a $\times 50$ lens to
14 focus the beam on the sample surface. A silicon reference wafer was used for calibration with the
15 reference peak at 520 cm^{-1} . Spectral resolution was on the order 2 cm^{-1} and power was limited to
16 under 100 mW to avoid heating the surface and affecting sample composition. Beam area was set to
17 around $1\text{ }\mu\text{m}^2$. Spectra were obtained from five 30 s acquisitions over the inclusion and five 30 s
18 acquisitions over the metallic matrix. The signal from the metallic matrix was then subtracted from the
19 inclusion signal. Spectrum acquisition was performed in Wire 3.4 and the baseline was established
20 using the included Cosmic Ray Remover software. Data processing was undertaken in Origin Pro
21 2016. The obtained spectra were compared with published reference spectra (Weber et al. 2015).

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

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

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

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

44 ██████████ Provenance attribution

45 Provenance was established by direct comparison of trace element content of slag inclusions with
46 smelting slag and iron ore of known origin. This method requires consistent concentrations of
47 elements between ore, slag and slag inclusions. As such, not all elements detected by LA-ICP-MS are
48 usable. Some elements (known as *siderophiles*) preferentially bond with the iron during the smelt and
49 are therefore overrepresented in the metallic iron. LA-ICP-MS analysis often accidentally ablates a

1 small portion of the iron matrix meaning that any provenance attribution relying on *siderophile*
2 elements will be skewed by this overrepresentation. In addition, some elements can show excessive
3 variance even after conversion to X_{ij} values. The choice of elements for this study was based on the
4 findings of Leroy (2010) and Disser (2014): Y, La, Ce, Yb, Nd, Pr, Gd, Sm, Dy, Eu, Th and U.

5 This study follows the example of Disser et al. (2016) and uses an unsupervised method of data
6 analysis. A supervised method would require manual categorisation of the data prior to analysis. This
7 approach works best when all finds are known to be of a single origin, but it can bias interpretation.
8 For example, a preliminary categorisation of ore based on geographic origin could obscure differences
9 between chemically distinct but geographically close ores and vice versa. Unsupervised methods of
10 data analysis allow a categorisation based directly on chemical data: samples are ranked by chemical
11 similarity and the obtained data is then reviewed manually to establish groups that best reflect the
12 samples. The method of analysis chosen for this study was Hierarchical Clustering of Principal
13 Components (HCPC, c.f. Husson et al., 2010). Once converted to X_{ij} values, a preliminary PCA was
14 performed to “de-noise” the dataset. The results were run through an HCA, which was the primary
15 method of establishing provenance. Provenance attribution was the same as group attribution for the
16 major elements: if two analyses were attributed to a common branch of the resulting dendrogram
17 below the user-defined threshold, they were assumed to have a common origin. Finally, the results
18 underwent a second PCA to represent the data in Cartesian coordinates.

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

32 ██████████ Selected ore and slag for comparison

33 Analyses of ore and slag were chosen on the likelihood of a connection with Oegstgeest (see
34 Figure []). As detailed previously, the Netherlands, in particularly the Veluwe, are a likely candidate for
35 the iron used at Oegstgeest. However, while ore and slag from the Veluwe has been extensively
36 studied (Joosten 2004), the available data focuses on *siderophile* elements. Due to the
37 aforementioned risk of over-representation of these elements due to accidental ablation of the iron
38 matrix, this makes the available data for the Veluwe incompatible with the methods of this study. As
39 such, the Veluwe was not included but was borne in mind as a possible origin for otherwise
40 unattributed samples.

41 The samples that were included came from regions in the broader Rhine and Meuse river
42 systems. In particular, this included ore from the Condroz in southern Belgium, characterised by
43 Pagès et al. (2022). Pagès et al. analysed 39 smelting slag from this region (detailed in Table []),
44 differentiating between slag from the Eastern Condroz and Entre-Sambre-et-Meuse in the Western
45 Condroz. This is because the latter area extends into areas that contained no iron ore but did contain
46 some smelting sites.

47 Additional samples came from Lorraine in Eastern France, based on ore and slag characterised
48 by Disser et al (2016). Iron production in Lorraine relied on a wide range of metallogenic contexts,
49 different kinds of sedimentary ore, as well as siderolithic and vein ores. Geological and archaeological
50 context of the included provenance spaces are described in Table []. Two provenance spaces
51 described by Disser et al. (2016) were not included. The Bajocian-Bathonian ore corresponded to
52 material from only two sites and the ore and slag from St-Dizier was characterised by only one site.

1 These were determined to be too small to be sufficiently representative and were not included to avoid
2 skewing the results of the provenance study.

3 The final samples included in this study come from across Southern Germany characterised by
4 Dillmann et al. (2017) (detailed in Table []). This region was included in part due to its proximity to the
5 Rhine River, but also because of the connection between the Rhine and Danube rivers in the Early
6 Middle Ages. At this period, these rivers formed a major axis of transportation between Eastern and
7 Western Europe (van Es and Verwers 2010). Given the aforementioned contact established between
8 Oegstgeest and the Mediterranean by Theuws et al. (2021a), it is likely that the objects traded
9 between these regions took this route. It is plausible that iron was traded along the same route,
10 making southern Germany, the land between the Rhine and Danube rivers, an interesting candidate
11 provenance space to explore.

12 The mineral facies identified by Optical Microscopy in the slags from Oegstgeest match similar
13 examples described in the literature. SGD slag was comprised of fayalite with widespread presence of
14 wüstite dendrites. SFR was made of fayalite and globular wüstite as well as large quantities of other
15 iron corrosion products that were unable to be identified. SAS showed a mostly vitrified microstructure
16 with occasional iron prills caught in the glassy matrix. The SCD microstructure identified by Disser
17 (2019) was indistinguishable from SGD as it was also comprised of fayalite with wüstite dendrites,
18 though these hearth bottoms did appear to contain more spinels. Subsequent SEM-EDX analysis
19 found that these were all iron oxides at concentrations consistent with magnetite. There was one
20 exception to this trend as OEG 283B presented a different microstructure. Macroscopically, the slag
21 was a complete circular hearth bottom with a thin cross section (~2 cm). Rather than the ubiquitous
22 fayalite and wüstite observed in other slags, its microstructure was dominated by spinels and needle
23 like crystals. SEM-EDX analysis found many of these to be comprised of Oxygen, Iron and Aluminium,
24 suggesting that these are hercynite. However, other minerals identified in the same slag either did not
25 contain iron, or contained higher concentrations of Magnesium and Calcium, suggesting the presence
26 of a wide range of minerals in this slag.

27 Several slag samples contained clear strata between different slag facies and this was especially
28 noticeable in OEG 5047 and 5052. These slags were not hearth bottoms and were included for
29 analysis in the hopes of identifying an unusual blue surface deposit. Their microstructure was almost
30 identical with both comprised of a lower SGD stratum and an upper SAS stratum, which contained the
31 blue colouration. Furthermore, optical microscopy identified a beige surface deposit adhering to the
32 SGD strata in both slags. SEM-EDX analysis found this deposit to be an iron sulphide, seemingly the
33 same in both samples, possibly pyrite (FeS_2 , see table []). The lower SGD strata contained fayalite
34 and wüstite dendrites though the latter presented unusually angular edges, not noted in any of the
35 other slags. This could indicate that the wüstite is euhedral. Despite the blue colouration, the SAS
36 strata optical microscopy was unable to distinguish the SAS stratum with other such examples seen in
37 the slags from Oegstgeest, though SEM-EDX did find higher concentrations of calcium.

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

48 3.2.

49  Nails

50 No clear distinction was found between the nails and boat nails, either by optical microscopy or
51 major element HCP. Both boat nails had relatively low carbon content with OEG 164 being ferrite with

1 some patches of hypo-eutectoid steel and OEG 221 being entirely ferrite. No welds were identified in
2 either sample. These same features were observed in almost all the other nails and are consistent
3 with bloomery steel samples described in the literature. The only exception was OEG 2611, which was
4 a mixture of ferritic iron and hypo-eutectoid steel but contained a weld identified by major element
5 HCP. Inclusions on either side of the weld line were attributed to separate groups, suggesting the use
6 of multiple blooms. Etching with Oberhoffer's reagent revealed ghost structures in all but one of the
7 nails (OEG 2540) indicating the use of phosphoritic iron. The extent of these structures varied
8 considerably from sample to sample, from a minimal presence in OEG 180B to extensive structures
9 across the entire sample in OEG 2546.

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

16 *Forge scrap*

17 The two pieces of forge scrap presented very different microstructures; OEG 583 (offcut) was
18 entirely ferrite with equiaxed grain (~200 µm diameter). The piece showed a clear uptick on one end,
19 characteristic of an offcut (Anderson et al. 2003). In contrast, OEG 5355 (bar) presented a mixed
20 microstructure: two bands of ferritic iron surrounding a central band of steel. The low proportion of
21 inclusions in this sample (only 2.3% of the sample surface, most of which were corrosion product)
22 made meaningful attribution of inclusions to chemical groups by HCP difficult. The forge inclusions
23 along the weld were attributed to a separate group but there were too few inclusions in the rest of the
24 sample to effectively interpret the data. The presence of a weld in this sample is evident from optical
25 microscopy though it is uncertain whether the iron was folded around a steel core or if two separate
26 pieces of iron were used. Oberhoffer etch found ghost structures in the upper ferrite band of OEG
27 5355, making it the only non-nail to present such structures. This same section showed a mixture of
28 fine grain ferrite with bands of hypo-eutectoid steel. The lower ferrite section was entirely large grain
29 with no carbon structures visible from nital etching. The central band was eutectoid steel with a slight
30 decrease in carbon content along the centre (see figure []).

31 *Composite objects*

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

38 OEG 968 sub 1 (fire striker) had the highest carbon content of any sample as the entire piece was
39 either eutectoid or hyper-eutectoid steel. The spine and the working edge were separated by a long
40 series of inclusions that appear to run the length of the sample. These were attributed to a distinct
41 class by the major element HCP due to differences in Mn and Na content (see figure []). However,
42 these inclusions do not appear to be a weld. Their large size, lack of wüstite and elongated rather than
43 globular shape all indicate that these are smelting inclusions. The entire working edge of the sample
44 presented martensitic structures, indicating that the piece had been quenched. However, a section of
45 the working edge presented cementite grain boundaries. (see figure [])

46 *Unidentified sample*

47 OEG 180A was neither a finished object nor forge scrap; it was entirely ferrite though without a
48 clear grain structure. Instead, the ferrite had a globular appearance and disaggregated into the
49 extensive inclusions (29.8% of surface) as well as into patches of the slag gangue that adhered to the
50 surface. This sample contained very few silicon rich slag inclusions, as seen in the other samples, and
51 instead contained spherical beige inclusions that were unable to be identified by OM. SEM-EDX

1 analysis found that these were iron sulphides (67 wt% Fe and 33 wt% S). Additional characterisation
2 was undertaken by Raman spectrometry. The resulting spectrum was unclear and lacked the
3 characteristic peaks of iron sulphides between 250 and 300 cm^{-1} though these results are consistent
4 with Pyrrhotite (Fe_7S_8) (see figure []). However, the lack of resolution in this spectrum, combined with
5 the measured Fe and S content being different than the predicted values for pyrrhotite (60.4 wt% Fe
6 and 39.6 wt% S) indicate that multiple iron sulphides are likely present.

7 ██████████ *Intra-site comparison*

8 Initial runs of the trace element HCPC found that the chemical variation of inclusions from
9 OEG 180A was very large and it was decided to remove this sample from the intra-site comparison to
10 avoid skewing the overall results. Intra-site comparison established 7 groups though the high chemical
11 similarity of inclusions within individual samples could indicate that each sample should be attributed
12 to individual groups (see figure []). The only sample to be attributed to two separate groups was OEG
13 968 sub 2, which is unsurprising in light of the weld identified by major element HCP in this sample. A
14 quarter of the inclusions from this sample matched with OEG 2611 and 5355, meaning that the
15 resulting group contained most entries from samples known to contain forge inclusions. Subsequent
16 visual confirmation by optical microscopy found that the respective ablations were overwhelmingly
17 performed on forge inclusions, meaning that these are unfortunately unexploitable for the provenance
18 study.

19 ██████████ *Inter-site comparison*

20 Individual comparison of finds against the full range of candidate provenance spaces found very
21 few clear groupings of slag inclusions from Oegstgeest with these sources. Only three samples were
22 placed in a common group with entries other than those from the same sample. Two samples, OEG
23 221 and 435, which were grouped together by the intra-site comparison, matched with samples from
24 Bayerische Schwaben. However, the second round of HCPC attributed both of these sets of inclusions
25 to groups containing only entries from the respective samples. The only firm attribution, in which the
26 inclusions from the sample were indistinguishable with the entries of ore and slag, was OEG 968 sub 1
27 (fire striker). Initial HCPC comparison against the full range of candidate provenance spaces grouped
28 the sample with entries from Swabia, Barrois, Minette and Fer Fort. A second HCPC was undertaken
29 with these entries which grouped OEG 968 sub 1 with entries from Fer Fort. Subsequent HCPC was
30 unable to distinguish between these entries, suggesting a common origin.

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

34 The metallurgical study revealed relatively advanced techniques such as welding and quenching
35 without any of indications of poor execution (peripheral oxidation, trapped corrosion product or splitting
36 along the weld line). Furthermore, OEG 5355 is a direct weld between iron and steel; these metals
37 weld at different temperatures and maintaining both pieces at the correct heat while undertaking the
38 weld would have required considerable experience (Fluzin 2002). This could indicate that the smith (or
39 smiths) at Oegstgeest were sufficiently experienced to undertake these operations though it is difficult
40 to confirm whether this would have taken place at the settlement. It possible that finds such as OEG
41 968 sub 1 (fire striker), could have been imported to the site as finished objects. This possibility seems
42 all the more plausible given the extensive pre-existing evidence for trade and importation of finished
43 goods at Oegstgeest. In contrast, it seems less likely that pieces of forge scrap, like OEG 5355 were
44 imported as such finds are typically associated with iron working in their immediate vicinity.
45 Furthermore, the presence of SAS slags, such as OEG 2001 sub 1 do indicate that such high
46 temperature activities did take place on site.

47 The metallurgical study revealed another interesting aspect of the iron at Oegstgeest, namely the
48 use of homogeneous steel, often with high carbon content. The steel used in OEG 968 sub 1 (fire
49 striker), 968 sub 2 (possible knife fragment) and 5355 (iron bar) was eutectoid to hyper-eutectoid.
50 Examples of such high carbon steel in the ancient world do exist (Godfrey and van Nie 2004) but
51 these tend to be relatively rare, or attributed to specific kinds of objects. For instance, the presence of

1 homogeneous high carbon steel in OEG 968 sub 1 (fire striker) was predictable as similar
2 microstructures have been previously observed (Terekhova and Zavyalov 2019). The use of such
3 homogeneous steel in OEG 968 sub 2 and 5355, as well as in lower carbon pieces such as OEG 968
4 sub 3 and 2540 was not expected and its use could indicate that metal of this quality was sufficiently
5 available at Oegstgeest to be used in objects as common as nails. In any case, these results suggest
6 that these materials, or the finished objects made from such materials, were available to the
7 inhabitants of Oegstgeest.

8 ██████████ *Copper content*

9 The copper prills observed in the hearth bottom OEG 603 are broadly similar with examples noted in
10 the literature (Eliyahu-Behar et al. 2012; Vodyasov et al. 2021). However, the described examples
11 were metallic copper rather than copper oxides and were an entire order of magnitude smaller (10-100
12 μm compared to ~ 1 mm diameter prills observed in OEG 603). Whether these prills were already
13 corroded upon entry to the slag or whether they oxidised during sample preparation is difficult to
14 establish. However, given that one of these prills is surrounded by a second, and that they both
15 present the same surface enrichment, it seems likely that these formed sequentially as liquid copper.
16 The smaller metallic copper prills found at the surface of the slag are more consistent with those
17 described in the literature. It is possible that this surface sediment is formed in part by the remains of
18 the hearth lining, in which case it would suggest that copper was sufficiently present in the hearth for
19 this sediment to find itself attached to the resulting slag.

20 There are two plausible sources for the origin of this copper. The first is brazing, in which deliberate
21 use of copper to attach two pieces of iron could have resulted in a portion dripping into the hearth.
22 However, given the clear evidence for copper recycling at Oegstgeest (Theuws et al. 2021b), the
23 possibility of tandem iron and copper working in the same hearth seems more likely. It is possible that
24 a spill would have led to the presence of metallic copper in the hearth which would have then been
25 incorporated into the forge slag. One of the main questions surrounding polymetallurgy at Oegstgeest
26 was whether iron and copper were being worked during the same phase of occupation. If the
27 presence of these prills is indeed an indication that iron and copper were worked in tandem, this not
28 only confirms that the metals were worked during the same phase of occupation, but potentially even
29 the same day. Furthermore, it implies that Oegstgeest had sufficient resources to either maintain two
30 artisans working in parallel, or that at least one smith had experience with both metals.

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

41

42 ██████████ *Sulphur content*

43 Despite the differing stoichiometric ratios of iron and sulphur between these samples, the
44 presence of the iron sulphide deposit in OEG 5047 and 5052 could be explained by the forging of
45 samples which contained large numbers of iron sulphide inclusions, such as OEG 180A (Craddock
46 and Lang 2005). However, as no other such samples were found at Oegstgeest, this remains
47 speculative. Nevertheless, OEG 180 A remains interesting as the sample most resembles a “gromp”, a
48 small fragment of iron bloom. This could be taken, alongside the possible smelting slag found at
49 Oegstgeest, as evidence of some smelting activities in the areas. However, the distinct lack of
50 smelting structures preclude the possibility of smelting within the settlement and both of these finds

1 are [outliers], meaning that this interpretation can again, only be speculative. Nevertheless, its
2 presence at Oegstgeest does raise the question of the origin of these sulphide inclusions.

3 High sulphur concentration in iron is typically provided by the ore (Craddock and Lang 2005) but
4 some sulphur rich fuel sources can produce iron sulphides, specifically coal. Within the Netherlands,
5 coal use is documented during the Roman period with evidence of smithing slags containing coal in
6 the settlements of Vechten and Kesteren (Joosten 2001, 2004, Hessing et al. 1977). Coal use
7 decreased in the Early Middle Ages, a trend noted across Western Europe at this time (Jagou 2020)
8 but it is possible that small-scale coal use continued into the Merovingian period. However, coal use is
9 typically limited to forge activities and the shape and distribution of these inclusions indicate that they
10 originated during the smelt. Furthermore, none of the forge slags from Oegstgeest match the typical
11 facies of coal forge slags, i.e. no coal or jarosite inclusions and relatively dense morphology (Jagou
12 2019). This does not completely rule out the possibility of sulphur contamination from the fuel as
13 Stepanov et al. (2022) found that sulphur contamination of wood charcoal can lead to the formation of
14 pyrrhotite inclusions in the iron bloom.

15 This leaves the ore as a possible source of sulphur, which raises several questions. Stepanov et
16 al. (2022) also found that despite a beneficiation regiment (roasting, hydro panning and sorting), it is
17 possible for sulphur rich ores to retain a portion a significant portion of the sulphur during the smelt. It
18 is also possible that the smelters were using especially sulphur rich ores in the first place. Tumiati et
19 al. (2005) studied a collection of 9th century slags produced using Servette-Chuc ore, a Pyrite (FeS_2)
20 rich ore with occasional “flames” of chalcopyrite (CuFeS_2) from the Val d’Aosta in Northern Italy.
21 Rather than spreading evenly throughout the bloom, sulphur was found as troilite (FeS) inclusions
22 caught within the iron matrix. This raises some possibilities as to the origin of this ore: most Dutch ores
23 are found in sedimentary contexts (Joosten 2004) which can result in some pyrite deposits though the
24 use of chalcopyrite could also potentially explain some of the copper observed in the slag inclusions of
25 OEG 180B and 2540 (nails). This copper would require a volcanic origin, placing the closest possible
26 source of ore in the Eifel. This would be a considerable distance to transport metal unfinished
27 materials, and also raises the question of why the settlement would have bothered importing such
28 poor iron when the even carbon distribution noted in many of the samples suggests that quality metals
29 were available, but this hypothesis remains consistent with the results of this study.

30

31 The provenance study was largely inconclusive. Despite the firm link established between OEG
32 968 sub 1 (fire striker) and Lorraine (Fer Fort), none of the other samples were able to be definitively
33 associated with any source of iron. It is likely that the iron used at Oegsteest came from sources not
34 considered by this study. As previously mentioned, the wider Netherlands, specifically the Veluwe,
35 are an extremely likely candidate for any worked at Oegstgeest and should compatible
36 characterisation of this ore be published, it is probable that at least one of the objects from Oegstgeest
37 will match this candidate provenance space.

38 It is possible that different Dutch sources, such as the Veluwe and bog iron ore, could account for
39 the full range of chemical variation seen at Oegstgeest but the clear evidence of wider contacts seen
40 at Oegstgeest through the study of other materials (Kars et al. 2018; Theuws et al. 2021a) indicates
41 the possible use of iron of other sources. Two regions stand out in particular:

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

47 Another conceivable source of iron is the Danube. Data from this region was not included in this
48 study due to its geographic distance from Oegstgeest. However, in the Early Middle Ages the Rhine
49 and the Danube formed the main axis of communication linking Eastern and Western Europe (van Es
50 and Verwers 2010). Contact between Oegstgeest and Eastern Europe seems likely given its location
51 at the mouth of the Rhine River and the presence of Mediterranean artefacts within the settlement. To

1 reach the Rhine (and by extension Oegstgeest), these artefacts would have passed through the land
2 between the Upper Rhine and the Upper Danube, which is Swabia. While OEG 221 and 435 were
3 unable to be formally associated with Swabian ore and slag, it is possible that Danubian iron (either as
4 finished objects or semi-products) could have been traded to Oegstgeest.

5

6 The study of both the slag and metal samples supports the conclusions of Disser (2019): the
7 creation and upkeep of finished objects appears to have been the primary form of iron working at
8 Oegstgeest. The presence of homogeneous steel at Oegstgeest, as well as complex objects like fire
9 strikers, suggests that quality goods and materials were available to the inhabitants of the settlement.
10 This is backed by the other imported goods found at Oegstgeest (Theuws et al. 2021a). Furthermore,
11 the use of advanced techniques like direct welding of iron and steel, as well as likely tandem iron and
12 copper working, suggests that at least one of the smiths had the training required to produce complex
13 objects using these materials.

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

19 Fer Fort from Lorraine was established as a likely source of iron used at Oegstgeest and an
20 additional tentative connection was made with Swabia. However, most of the samples remain
21 unattributed and these appear to be made from iron of several different sources. Should compatible
22 data become available, these would benefit from a comparison with the Netherlands, England and the
23 Danube.

24 In summary, the findings of this study further support the conclusions of Kars et al. (2018) and
25 Theuws et al. (2021a): far from being a poor and isolated settlement lost in a “marginal landscape”, the
26 site was well-connected, both within its local region and within wider networks of exchange spanning
27 the European sub-continent. At least from a metallurgical point of view, Oegstgeest was fully
28 integrated into both local regional networks of exchange.

29

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Figure titles and descriptions

- 1
- 2 Figure 1. Map of the Merovingian settlement at Oegstgeest (Theuws et al. 2021a).
- 3 Figure 2. a. OEG 221, SCD hearth bottom from Oegstgeest retaining the clear shape of the hearth. b.
4 OEG 2352. One of the tap slags from Oegstgeest with a knotted surface and broken edges.
- 5 Figure 3. List of the different sources of ore and slag compared to the Oegstgeest samples and their
6 geographic location.
- 7 Figure 4. One of the copper oxide prills in OEG 603. This specific prill is comprised of one larger prill
8 surrounding a smaller prill (a.), suggesting that these formed sequentially, likely in the hearth. The
9 surrounding facies was typical SFR (b. wüstite dendrites, c. glassy matrix). The composition of the prill
10 is summarised in Table 3.
- 11 Figure 5. OEG 5047. a. Macroscopic view showing the vitrified blue SAS patches on its surface. b.
12 Boundary between the SAS and the SGD strata. The neat delineation between the two strata indicates
13 that they formed sequentially but given that the fayalite continued to form further into the SAS stratum,
14 this must have been while the SAS was at least partially liquefied. The yellow/white microstructure on
15 the right was identified as an iron sulphide compound by SEM-EDX. Given that the edge of this
16 surface enrichment is perfectly aligned with the split between SGD and SAS, this deposit seems to
17 have formed after the SGD section but before the SAS section, suggesting that it likely took place in
18 the hearth.
- 19 Figure 6. The microstructure of OEG 2352. This piece contained relatively little wüstite compared to
20 the forge slag but it did have lines of wüstite running through the sample. These were likely surfaces
21 exposed to air, which oxidised before being covered with fresh slag.
- 22 Figure 7. Etched microstructure of a. OEG 968 sub 3 and b. OEG 2540. Both samples were made of
23 hypo-eutectoid steel and had unusually even carbon distribution across the piece.
- 24 Figure 8. OEG 2611. SEM-EDX analysis split the inclusions from this sample into three groups that
25 are located in three discrete regions across the sample surface, suggesting that the sample is likely
26 made of two blooms (red and blue inclusions) separating by forge inclusions (yellow).
- 27 Figure 9. OEG 5355. This offcut contained a clear weld between iron and steel.
- 28 Figure 10. OEG 968 sub 2a. The three inclusions marked in red were attributed to a separate class by
29 HCPC. The other three inclusions were in the corresponding location on the other side of the piece,
30 which was analysed as a separate sample (OEG 968 sub 2b, see supplementary material).
- 31 Figure 11. Microstructure of OEG 968 sub 1. a. Tempered martensite located along the working edge
32 of the piece. b. Hyper-eutectoid steel located along the rear edge. c. Cementite that formed along the
33 grain boundaries in the lower edge of the quenched working edge.
- 34 Figure 12. Iron sulphide inclusions in OEG 180A. Most inclusions were small and spherical but some
35 were larger and disaggregated into the iron matrix.
- 36 Figure 13. Results of Raman spectroscopy of iron sulphide inclusions in OEG 180A.
- 37 Figure 14. Dendrogram resulting from HCPC of intra-site provenance. The red line indicates the
38 threshold above which objects are considered to belong to a separate group. Objects grouped
39 together are circled in red and attributed a group number.
- 40 Figure 15. Crater resulting from LA-ICP-MS ablation in one of the inclusions in OEG 2611. The linear
41 shape and large amount of wüstite in this inclusion could indicate that it is a forge inclusion. The
42 analysed inclusions in OEG 2611 and 5355, as well as the six inclusions identified as separate in OEG
43 968 sub 2 showed similar facies. This suggests that these were all accidental ablations of forge
44 inclusions and therefore cannot be used in the provenance study.

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Table titles and descriptions

3 Table 1. List of samples analysed in this study, specifying the methods by which they were studied.

4 Table 2. Synthesis of petrographic study.

5 Table 3. Composition of the copper prill shown in Fig. 4. a. as established by SEM-EDX.

6 Table 4. Synthesis of the metallurgical study.

7 Table 5. Synthesis of provenance results.