Slag characterization from the Roman vicus of Eisenberg (Germany)

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Received: 14 March 2022 / Accepted: 23 June 2022 / Published online: 22 July 2022
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Abstract
The Roman vicus of Eisenberg in Rhineland-Palatinate (Germany) has always been considered to be an important Roman iron smelting centre due to numerous slag finds and relics of furnaces. Most excavations that revealed iron working debris have been performed in the nineteenth or early twentieth century. Their results and interpretations have been considered to be doubtful, but more recent excavations have brought to light further relics of iron working processes, which have not, however, helped to clarify the situation. Therefore, slag and ore fragments from two locations of discovery were selected for investigation, because no systematic investigations have been carried out on slags or other relics of iron working so far, despite the enormous importance of such a place. The first results of this investigation clearly prove the smelting of iron in slag-tapping furnaces during Roman times due to the morphology of the slag, but they also show that the metallurgical debris is obviously not in situ and has been used as filling material. In addition, the high-grade haematite ores also found on the ground could serve as a source for smelting.

Keywords Roman iron production · Slag · Slag-tapping furnace · Optical microscopy · WDXRF · XRD · SEM/EDX

Introduction
The importance of iron production in the Roman world is obvious, as the demand for military equipment, public responsibilities, and civil requirement must have been enormous. Weapons, armoury, a large variety of tools, agricultural implements, structural fittings for architecture or means of transport, and nearly all basic commodities were made of iron (e.g. Dolenz 1998; Hanemann 2014; Manning 1985; Pietsch 1983; Pollak 2006; Schütz 2003). J. Lang (2017) has more recently reviewed the variety of applications of ferrous materials in Roman times that ranges from delicate surgical instruments to heavy lumps for buildings and naval devices. It can therefore be assumed that very sizable quantities of iron ores were mined and smelted in the Roman provinces to cover regional to trans-regional demand and not only for the needs of the immediate vicinity. For the trade of iron, unconsolidated blooms may have been circulated to a certain extent, but semi-finished products were shaped into more convenient forms for transport or sale. Indeed, numerous iron bars are known from Roman settlements, hoards, and mainly from shipwrecks from the Mediterranean Sea, which evidence the intensive trans-regional trade in iron during Roman times (Parker 1992; Feugère and Serneels 1998). Such billets may have been additional supply or a specific material of guaranteed quality that could be recognized by the intermediaries and by the final producer of iron implements by the shape of the billets (Pagès et al. 2011). Apart from that, cargos with several hundred of kilogrammes of iron have been substantial batches, which may have made intensive local iron production unnecessary or less intensive in many regions. Actually, we do have ample evidence for Roman iron working from all over the Roman Empire, as it is expected in view of the large quantity of iron used, but most iron working debris belongs to smithy workshops (Pleiner 2006). Roman iron smelting sites are much less documented, and elements of evidence appear quite questionable, because
of the poor documentation of the metallurgical relicts, often excavated during the nineteenth or early twentieth century (e.g. Weiershausen 1939). The evaluation of such relicts with regard to quantification and classification due to the metallurgical processes they derive is difficult or impossible only by published information. Usually, archaeologists assessed such metallurgical waste quite arbitrary and without scientific proof.

Roman writers refer to iron smelting on the Iberian Peninsula, Elba, or Populonia and particularly to the Noricum as the provinces in which iron has been produced on a large scale (Domergue 2008; Pleiner 2000). Steel from Noricum, the Ferrum Noricum has been celebrated by antique writers over centuries, but there is now archaeological evidence for iron production on a large scale (see Chech 2008; 2017; Furger 2019). Indeed, there are many more areas within the Roman Empire known to date in which iron was demonstrably produced in huge quantities. These include smelting centres on the British Isles like the Weald of Sussex, the Forest of Dean and in the East Midlands (Cleere 1983; Cleere and Crossley 1995; Hodgkinson 2008; Paynter 2006; Schrüber-Kolb 2004), in Gaul (Domergue 2008; Domergue et al. 2006; Dunikowski and Cabboi 1995; Polfer 2000), or in Illyricum and in Moesia Superior (Cleere 1983; Domergue 2008; Hirt 2010).

The situation appears different in other provinces, which may be due to the state of archaeological research or can simply also contradict the truth, in that no or little iron production took place there. The region along the Limes Germanicus, which has been the eastern border of the ancient Roman provinces of Germania Inferior, Germania Superior, and Raetia, is such an area with evidence for intensive iron working, but again, proofs for iron smelting are poor. Sernees (2014) has summarized the results of intensive research into iron working debris on the Swiss plateau, which belonged to the Raetia province, revealing substantial evidence for iron working, but none or rather scarce and uncertain evidence for iron smelting during Roman times. Polfer (2000) delivered a bibliographical catalogue and a map of iron working sites from the Northern Gaul and the Roman part of the territory of the present-day Federal Republic of Germany. His information is mostly based on the presence of slag, furnace residues, and supposed ore lumps without any scientific proof. More recently, Gassmann and Schüfer (2014) have summarized the state of research and pointed out that intensive iron smelting in this area had almost been practised exclusively outside the Roman Empire, in the Germania Magna by Germanic tribes. According to them and the other published information, it seems that there is something between two or maybe four places with more or less secure evidence of Roman iron smelting along the Limes border. One of these places is near Bad Neuenahr-Ahrweiler in the Eifel Mountains in the ancient Roman province of Germania Inferior. Within a Roman villa, 16 furnaces have been excavated, which are declared to be smelting furnaces, while other furnaces are interpreted to be reheating or smithing hearths (Kleemann 1978; Ritzdorf 2006; Saal 2012). Most of the furnaces come from one house and were constantly replaced (Ritzdorf 2006). Slag is found within the houses and as slag heaps in the surroundings (Ritzdorf 2006; Saal 2012). This place is believed to be the only one within a larger iron smelting area of around 20 km² (Polfer 2000). The other place with a long research history is the vicus of Eisenberg in Rhineland-Palatinate, which is the research focus of our work to find out its importance as an industrial site location.

Archaeological background

The Roman vicus of Eisenberg was located on the eastern edge of the North Palatinate Mountains, in the so-called Eisenberg Basin south of the Donnersberg, the highest peak of the Palatinate Mountains. This is an area that sank in the Tertiary period, in which thick layers of clay and sand, so-called luting sands, were deposited over the time, which were excellently suited for refractory ceramics and which are still used industrially today.

Research on the Roman Eisenberg has a long history. A first high point reached with the work of Christian Mehlis and Friedrich Sprater in the second half of the nineteenth century and at the beginning of the twentieth century. Both were intensively involved with the Roman settlement and carried out excavations in the area of the vicus and the late antique burgus. Their publications have a decisive influence on today’s image of Roman Eisenberg (Mehlis 1883; Sprater 1919; 1952; Bernhard 1990; Him elmann et al. 2016). A second phase of intensive research began in 1992, when the construction of a ring road made large-scale excavations necessary, during which a considerable part of the Roman town centre was investigated (Kreckel 1998, 2004; Himmelmann 2006; Heidelberg Braun 2022; Bernhard et al. 2007; Tenzer 2010). Between 2012 and 2018, several teaching excavations of the University of Heidelberg were carried out in the area of “House 22” and at the late antique burgus (Schönenmann 2018a; 2018b).

Geographically, the settlement is located on the northernmost Roman east–west connection between the Rhine plain and Lorraine. This important road passed through the Kaiserslautern Basin and connected the cities of B Orbetomagus (Worms) in the province of Germania Inferior and Divodurum Mediomaticorum (Metz) in Gaul (Fig. 1). A settlement developed in the area of the later Roman centre between the penultimate decade of the first century BC and the last third of the first century AD. Although some late Iron Age (Latène period) features could point to a history
of the site going back even further, these clues are still relatively vague so far (Kreckel 2004; Himmelmann 2006). The early settlement, with irregular, small-scale woodwork house constructions, which were already oriented towards the later traffic axes (Fig. 2), has so far been documented in an area of about 700 m² in the centre of the later vicus (Braun 2019; Braun et al. 2019). However, the early Roman site could also have been larger, as some adjacent areas have not yet been investigated or have already been removed undocumented in the past. In the second half of the first century AD, possibly after 70 AD, the area of the early settlement was extensively flattened and then rebuilt (Bernhard et al. 2007). A small town settlement with so-called strip houses developed on the same site, which was again oriented along a main traffic axis and a side street branching off from it at an acute angle at the eastern entrance to the village (Fig. 2). In the centre of the settlement was a large building (44.50 × 26 m), which is interpreted as a market basilica with an open inner courtyard (Kreckel 2004). Immediately south of the public building was an open space, which can probably be interpreted as the central square of the settlement. To the west of the public building and the central square were the houses number 3 and 4. The slags examined in this work come from these two plots, from layers belonging to the early phase of the settlement. The settlement reached its greatest extent in the middle of the second century AD and then covered an area of 8 to 12 hectares, although the first buildings seem to have been abandoned by the end of this century (Bernhard et al. 2007; Sprater 1952). A further decline can be observed in the advanced third century. In the middle of the fourth century, there is evidence of extensive destruction of the site, which could be connected with the riots by the usurper Flavius Magnus Magnentius between 350 and 353 AD.

Subsequently, coin-dated flattened layers document extensive demolition and clearing work for the years 364 to 370 AD (Bernhard et al. 2007; Kreckel 2004; Himmelmann 2006). These are probably connected with the construction

![Fig. 1 Location of the vicus of Eisenberg at the Rhine border and its connection with the central places within the region](image1)

![Fig. 2 Floor plan of the vicus of Eisenberg with mapping of traces of metalworking within the settlement area. The plots “House 3” and “House 4,” from which the samples come, are located immediately northwest of the central square (draft A. Braun after Bernhard et al. (2007))](image2)
Iron working in Eisenberg and its vicinity

Already, the name of Eisenberg (Iron Mountain) implies a connection with iron working or mining that must have been practised within or around the site in the past. There are several outcropping iron ore deposits in the immediate vicinity and small pits from open-cast mining and large slag heaps of thicknesses of up to five metres give evidence for mining and metallurgical activities (Mehlis 1883; Bernhard et al. 2007). The rich brown iron ore deposits, the so-called Stauf layers, which occur near the surface directly to the west of the Eisenberg basin, as well as the clay iron stones, which occur to the north, east and south of Eisenberg, could have been particularly important for economic success in Roman times (Braun et al. 2019), especially in the so-called Stumpfwald, which is part of the northern Palatine Forest in the west of Eisenberg with its remarkable slag heaps and fall shafts has always been considered as a Roman iron smelting area (Braun 2018; Braun et al. 2019; Sprater 1952; Walling 2005). Some surveys during the last years have shown that many of the assumed fall shafts were clay pits or bomb craters from the Second World War (Braun et al. 2019). Actually, the assignment of all these relicts to a certain period nor to a specific operation is still doubtful, as there have been different later activities and intensive clay-extraction during modern times. There is historical evidence for grinding mills from the fifteenth century AD and for a hammer mill from the early eighteenth century that has later been completed with a blast furnace, which ran until the late nineteenth century (Graf 1960; Walling 2005). Huge slag tips were frequently accumulated in the vicinity of blast furnaces, and parts of the slag heaps may derive from this process. The subsequent iron foundry is still active today. Open-cast mining pits may mostly derive from private miners supplying the early modern blast furnace, but some may also be older (Walling 2005).

Indeed, the published data of iron ores coming from Eisenberg and surrounding areas show variable quality, and most of them are not suitable for the bloomery process, but sufficient for a blast furnace process (Mehlis 1883; Sprater 1931/32; Braun et al. 2019).

Nevertheless, iron working activities in or around the vicus of Eisenberg are undoubted and have most probably been a major industry in Roman times, as metal working debris like slag, ore fragments, or technical ceramic is present as a filling material from the early Roman phase of the settlement. This occurrence of iron working debris within flattened layers from the first century AD (finding 2658; Himmelmann 2006) suggests pre-Roman iron working activities (Mehlis 1883; Sprater 1931/32). Even though it is a confusing situation, because all metallurgical waste that is certainly dated derives from secondary use and probably not from the smelting places or workshops directly. Slag was used to fulfil postholes (e.g. pit 2619), and roads were gravelled with up to 30-cm thick slag layers, which are covered with a final sandstone and slag paving (Himmelmann 2006).

The first excavations in the nineteenth century have revealed some remains of technical ceramics from a slag heap nearby the vicus that have been interpreted to be furnaces for iron smelting and other iron working processes (Mehlis 1883). A similar archaeological record has been reported by Sprater (1931/32), who interpreted these relicts as a roasting furnace. Weiershausen (1939), who has written the first textbook about ancient iron smelting in Germany, has criticized both interpretations and reconstructed shaft furnaces with slag pits and slag-tapping furnaces, which the latter would fit typical Roman smelting technology (e.g. Dunikowski and Cabboi 1995). More recent excavations have revealed two pits within house number 16 and some round stains in house number 4, which show some impact of heat (Bernhard et al. 2007). These and other findings are now interpreted as smelting furnaces according to those slag-pit furnaces from the early Romano-Barbarian site of Tuklaty in the Czech Republic (Braun 2019). Those furnaces are non-tapping sunken-floored or sunken hearth furnaces (Weiershausen 1939; Pleiner and Salac 1987; Pleiner 2000). Finally, at least nine other sites are known in the immediate vicinity of the early settlement with about 25 probable furnaces, as well as numerous accessible working pits. Some working pits, which are located in the direct vicinity of the furnaces, have internal postholes and can be interpreted as pit houses with a floor area of 3.3 to 4.5 m².

Evidence for a continuation of metallurgical activities in the Middle Roman Imperial period is lacking in the areas investigated so far. However, it is conceivable that these activities were shifted from the now more representative centre to the outer areas of the settlement, which have not yet been investigated or were undocumented destroyed in the late nineteenth and early twentieth centuries. However, the discovery of the base of a Jupiter giant column from the late second to mid-third century with a pictorial representation of Vulcanus, the god of fire and metalwork, supports that...
metallurgy was important at this site in the Middle Imperial period (Sprater 1929). On the other hand, Brommer (1973) has pointed out that Roman provincial reliefs of Vulcanus were mainly concentrated within this area between Metz, Mainz, and Karlsruhe in the south, suggesting a conflation with a local god and no comprehensible connection with local mining or smelting activities.

**Material and methods**

Slags are essentially the main waste product of the iron smelting process and accessible materials for research. They are valuable source of information for reconstruction of the process and materials applied, but other waste may deliver further information. Samples from metallurgical debris have been chosen for this first testing, coming from a selected archaeologically well-documented area. They all derive from the houses number 3 and 4 from layers belonging to the early phase 20 BC of the settlement with the youngest strata 158 AD (Table 1). The corpus of finds from these two houses has been checked optically for metallurgical debris. Slug material, one bloom, and some ore refuse looking red-brown or ochreous fragments were selected for scientific analysis. All slag material has been cleaned, weighted, and selected by morphological criteria, as good as the size of the slag allows. As mentioned before, all metallurgical waste had been deliberately crushed to small pieces, so that typical characteristic slag agglomerations like so-called “plano-convex bottoms” (“PCB”) or slag-pit blocks are not distinguishable anymore. Nevertheless, there are four different types of slag specifiable only by macroscopic observation (Fig. 3). The first type is noticeable by its prevailing red brown colour, high porosity, adhering charcoal and soil, and non-uniformity, which is usually a typical appearance of smithing slag (e.g. Allen 1986). The second type of slag is mainly grey-brown to black, with some adhering charcoal and a dense diffusely flown surface structure (Fig. 3). This kind of slag usually originates from non-tapping furnaces, as the diffuse solidification structure of the slag results from the solidifying on the bottom of the furnace (e.g. Paynter 2006; Schröfer-Kolb 2004). The two remaining types of slag show a very similar appearance and may originate from a slag-tapping furnace. Most of them are grey-black with purplish stains; they are much denser with small pores and have a clear flow texture, which can form rods, blobs, or plates (Fig. 3). Actually, the plate slag show a very distinct form, as they are only one to two centimetres thick, often with less than one centimetre thickness, with plane-parallel surfaces (Fig. 3). Therefore, plate slag and irregular shaped running slag have been separated into two groups. Both types are well documented for Roman period smelting sites inside the Roman Empire (Dunikowski and Cabboi 1995; Paynter 2006; Schröfer-Kolb 2004).

Slag samples and ore looking material have been sectioned, and one part has been crushed, powdered, and fused to beads for wavelength dispersive X-ray fluorescence analysis (WDXRF) for bulk chemical analysis. Chemical analyses of about 44 slag and ore samples has been performed by WDXRF (Bruker AXS S4 Pioneer spectrometer, Rh X-ray tube, 4 kW) with standard free calculation at the Department of Geoscience at the University of Tübingen. Analytical error and detection limits vary and depend on the element and uncertainties of sample composition. Uncertainties for all major elements are better than 1% (1SD) and for the trace elements are better than 5% (1SD). The results are given in Tables 2 and 3. Phase assemblages were identified by using powder X-ray diffraction (Bruker D 8 Advance) equipped with a Cu-X-ray tube running at 40 kV/20 mA, a Goebel mirror optics and a 1D-VANTEC-1 detector) at the Competence Center Archaeometry-Baden-Wuerttemberg (CCA-BW), at the University of Tübingen. Slag and ore fragments have been sectioned to suitable size by a diamond cut-off machine, mounted in low-viscosity epoxy resin under vacuum, and prepared as polished sections. They were examined with light optical microscopy (Zeiss Axioskop 40 A Pol) under reflected and polarized light and with scanning electron microscopy (ZEISS EVO 60 MA 25) with an attached silicon drift detector (SDD) for energy dispersive X-ray analyses (Bruker XiFlash) at the Curt-Engelhorn-Zentrum Archaeometry in Mannheim. The quantification is standard less by absolutely calculated concentrations without normalization (see Eggert 2006) and is regularly controlled by measurements of standards under defined and reproducible conditions. The accuracy of components in reference materials is between 1–2% for main and 5–20% for minor components.

**Results**

The macroscopic classification by morphology, density, and colour and weight calculation of the slag presents already one significant aspect: The majority of fragments have less than 100 g weight (Fig. 4), which is an appraisal factor. It again emphasizes its character as a filling material, crushed to small pieces that might has been transported to the locations of discovery, rather than remaining local working debris. Furnace slag, plate slag, and other running slag derive from the iron smelting process, but they can be associated with some smithing slag within the same archaeological record. According to their morphological designation, around 90% of the slag originate from the iron production by smelting and not from an iron working process.
The chemistry and phase assemblages of the slag reflect the input of the additives like ore, charcoal, furnace lining, or flux and form an index as to the redox conditions in the furnace (Bachmann 1982). Chemical and phase analyses (Tables 2, 3 and 4) reveal that despite of the obvious different morphology of the slag, there is no significant difference in the chemical composition or phase assemblages of the varying slag from the smelting process. The general viscosity index, defined by base to acid ratio (Bachmann et al. 1989), of the plate slag and other running slag is not significantly higher than of the furnace slag, even when tapped-slag must have been obviously liquid and could be removed.

| Box no | Dating                  | Feature                  | Finding                  | Lab. no |
|--------|-------------------------|--------------------------|--------------------------|---------|
| 22,915 | 20 BC until Common Era  | 3935/12                  | Plate slag               | MST17   |
|        |                         | 3935/13                  | Slag with flow pattern   | MST43   |
|        |                         | 3935/14                  | Smelting slag            | MST12   |
|        |                         | 3935/15                  | Smelting slag            | MST14   |
|        | 20 BC until AD 14       | 3940/1                   | Plate slag               | MST22   |
|        |                         | Slag with flow pattern   | MST30                    |
| 15,053 | Approx. 20 BC until AD 20| 196/2                    | furnace slag             | MST09   |
|        |                         | furnace slag             | MST10                    |
|        |                         | slag with flow pattern   | MST37                    |
| 15,055 | Approx. 20 BC until AD 20| 359/1                    | Furnace slag             | MST06   |
|        |                         | Slag with flow pattern   | MST41                    |
|        |                         | Slag with flow pattern   | MST42                    |
|        |                         | Plate slag               | MST26                    |
|        |                         | Plate slag               | MST27                    |
| 15,074 | Approx. 20 BC until AD 25| 440/1                    | Smithing slag            | MST15   |
|        |                         | Slag with flow pattern   | MST34                    |
| 15,052 | Approx. 20 BC until AD 40| 188/7                    | Plate slag               | MST28   |
|        |                         | Slag with flow pattern   | MST33                    |
| 14,971 | Approx. AD 25 until AD 50| 208                      | Smithing slag            | MST13   |
|        |                         | Plate slag               | MST19                    |
| 14,162 | Approx. AD 40 until AD 80| 17b                      | Bloom                    | MST16   |
|        |                         | 17b#49                   | Iron ore                 | MST05   |
| 23,704 | AD 40 until AD 80       | 4776/3                   | Plate slag               | MST20   |
|        |                         | Plate slag               | MST21                    |
|        |                         | Slag with flow pattern   | MST31                    |
|        |                         | Slag with flow pattern   | MST32                    |
| 14,956 | Earlier than the first half of the second century (post-hole, means dislocated slags) | 218                      | Furnace slag             | MST07   |
|        |                         | Furnace slag             | MST08                    |
| 15,061 | Earlier than the middle of the second century | 254/2                    | Smithing slag            | MST11   |
|        |                         | Slag with flow pattern   | MST40                    |
| 22,846 | Earlier than AD 158     | 3939/3                   | Plate slag               | MST29   |
| 15,350 | Unknown                 | 469/3                    | Sandstone                | MST01   |
|        |                         | Iron ore                 | MST02                    |
|        |                         | Plate slag               | MST24                    |
|        |                         | Plate slag               | MST25                    |
|        |                         | Slag with flow pattern   | MST38                    |
| 23,704 | Unknown                 | 4772/1                   | Plate slag               | MST18   |
|        |                         | 4772/2                   | Iron ore                 | MST03   |
|        |                         | Stone                    | MST04                    |
|        |                         | Slag with flow pattern   | MST35                    |
|        |                         | Slag with flow pattern   | MST36                    |
continuously from the hearth, while the furnace slag has just become pasty and collected in the bottom of the furnace. Indeed, some plate and running slags have a significant higher viscosity index due to their high iron oxide contents (>80%) and therefore a lower viscosity, but there is no general tendency visible. At the same time, some of the plate slags have the lowest iron oxide contents (<50%) and highest portion in silica (>30%). Therefore, the temperature dependence of the viscosity of the slag seems to be the ruling factor for the final morphology of the slag.

All slags are typical iron-rich fayalitic slags with skeletal and some massive crystals of olivine within a vitreous
matrix, where parts of the iron are replaced by manganese (Figs. 5 and 6). Therefore, the percentage of iron oxide is quite high (47–86%), and most slags have a composition near the composition of the dominant phase fayalite ($\text{Fe}_2\text{SiO}_4$) with some percentages of manganese (Tables 2 and 3). When iron oxide is in excess, the occurrence of some dendritic wüstite ($\text{FeO}$) and leucite ($\text{KAl}_2\text{O}_4$) showing eutectic textures of crystallization can be observed (Figs. 7 and 8) that indicate local low melting temperatures. Hercynite ($\text{FeAl}_2\text{O}_4$) is rarely observed and could only be detected in two slags (MST 10, MST 14, Table 4). All slags show very low phosphorus contents below 1%, and alkali oxides and alkaline earth oxides are present with some percentages, but there is no evidence for the addition of fluxes. The additional alkali support may derive from the fuel ash (Crew 2000), but in total, their share usually

| Lab. no | Artifact type | Ba  | Rb  | Sr  | V   | Y   | Zn  | Zr  |
|--------|---------------|-----|-----|-----|-----|-----|-----|-----|
| MST01  | ores/rocks    | 1066| 307 | 925 | 170 | 59  | 156 | 721 |
| MST02  |                | 319 | 98  | 156 | 36  | 69  | 206 | 491 |
| MST03  |                | 610 | 139 | 123 | 44  | 40  | 221 | 93  |
| MST04  |                | 1108| 16  | 1090| 28  | 16  | 228 | 89  |
| MST05  |                | 1006| 94  | 332 | 63  | 44  | 137 | 94  |
| MST06  | furnace slag   | 709 | 56  | 117 | 47  | 40  | 9   | 139 |
| MST07  |                | 1046| 190 | 305 | 61  | 25  | 125 | 528 |
| MST08  |                | 1082| 146 | 263 | 59  | 16  | 83  | 263 |
| MST09  |                | 207 | 27  | 150 | 21  | 106 | 132 |
| MST10  |                | 590 | 57  | 109 | 57  | 69  | 10  | 149 |
| MST11  |                | 539 | 211 | 466 | 54  | 34  | 169 | 441 |
| MST12  | Smithing slag  | 681 | 60  | 92  | 48  | 34  | 4   | 130 |
| MST13  |                | 258 | 35  | 317 | 25  | 121 | 142 |
| MST14  |                | 373 | 124 | 154 | 32  | 14  | 105 | 202 |
| MST15  |                | 142 | 24  | 94  | 5   | 29  | 90  | 52  |
| MST17  | Plate slag     | 779 | 150 | 356 | 56  | 36  | 150 | 295 |
| MST18  |                | 358 | 63  | 143 | 25  | 25  | 77  | 249 |
| MST19  |                | 96  | 27  | 95  | 11  | 94  | 163 |
| MST20  |                | 312 | 61  | 180 | 35  | 37  | 102 | 160 |
| MST21  |                | 665 | 56  | 231 | 28  | 92  | 189 |
| MST22  |                | 1024| 88  | 240 | 55  | 45  | 314 |
| MST23  |                | 1051| 119 | 293 | 65  | 33  | 8   | 369 |
| MST24  |                | 506 | 85  | 102 | 55  | 46  | 247 |
| MST25  |                | 658 | 107 | 314 | 78  | 27  | 31  | 162 |
| MST26  |                | 674 | 80  | 104 | 52  | 58  | 10  | 178 |
| MST28  |                | 734 | 87  | 161 | 57  | 42  | 9   | 146 |
| MST29  |                | 462 | 54  | 58  | 46  | 73  | 115 |
| MST30  | Running slag   | 471 | 69  | 169 | 53  | 48  | 10  | 424 |
| MST31  |                | 603 | 87  | 211 | 47  | 27  | 232 |
| MST32  |                | 529 | 71  | 162 | 55  | 59  | 352 |
| MST33  |                | 531 | 96  | 111 | 44  | 61  | 44  | 256 |
| MST34  |                | 672 | 26  | 60  | 38  | 35  | 7   | 160 |
| MST35  |                | 471 | 164 | 207 | 70  | 69  | 391 |
| MST36  |                | 454 | 42  | 160 | 37  | 43  | 3   | 391 |
| MST38  |                | 455 | 46  | 149 | 35  | 10  | 94  |
| MST39  |                | 451 | 69  | 216 | 34  | 98  |
| MST40  |                | 1341| 144 | 237 | 66  | 398 |
| MST41  |                | 1018| 95  | 168 | 70  | 61  | 112 | 464 |
| MST42  |                | 994 | 86  | 222 | 51  | 47  | 836 |
| MST43  |                | 546 | 151 | 287 | 68  | 42  | 19  | 194 |
remains well below 10%. Some plate and running slag with low iron contents show elevated amounts of alkali oxides (MST 23, MST 35, MST 40; Tables 2 and 3), but again, there is no general tendency visible. Pieces of unmelted quartz are mainly appearing on the external surface of the slag and do not influence the chemical composition.

Four samples have been assigned to smithing slag by morphological reasons, but according to their chemical
| Lab no | Find no           | Classification                          | Phases                                                                 | Methods                  |
|--------|-------------------|-----------------------------------------|------------------------------------------------------------------------|--------------------------|
| MST01  | 15,350–469/3–1   | aluminous and ferrous sand stone        | Quartz, haematite, muscovite, orthoclase, albite                      | XRF                     |
| MST02  | 15,350–469/3–2   | haematitic iron ore (red iron ore sandstone) | Quartz, haematite, muscovite, anorthite, orthoclase, goethite         | XRF, XRD                |
| MST03  | 23,704–4772/2–1  | goethitic and haematitic iron ore       | Hydroxyapatite                                                        | XRF, XRD                |
| MST04  | 23,704–4772/2–2  | Haematitic iron ore                     | Quartz, haematite, muskovite                                          | XRF, XRD                |
| MST05  | 14,162–17b49–1   | Haematitic iron ore (red iron ore sand stone) |                                           | XRF, XRD                |
| MST06  | 15,055–359/1–1   | Furnace slag                            | XRF                                                                   |                          |
| MST07  | 14,959–218–1     | Fayalitic furnace slag                   | Manganese fayalite, wüstit-Kirschsteinite-cotectic, glass            | XRF, LOM, SEM           |
| MST08  | 14,959–218–2     | Furnace slag                            | XRF                                                                   |                          |
| MST09  | 15,053–196/2–1   | Fayalitic furnace slag                   | Manganese fayalite, wüstit in 2 generation, ferrous glass            | XRF, LOM, SEM           |
| MST10  | 15,053–196/2–2   | Fayalitic furnace slag                   | Manganese fayalite, quartz, leucite, hercynite                       | XRF, XRD                |
| MST11  | 15,061–254/2–1   | Fayalitic furnace slag                   | Manganese fayalite, wüstit, glass phase                              | XRF, LOM, SEM           |
| MST12  | 22,915–3953/13–1 | Furnace slag                            | Manganese fayalite, wüstit, quartz, leucite                          | XRF, XRD                |
| MST13  | 14,971–208–1     | Smelting slag                           | XRF                                                                   |                          |
| MST14  | 22,915–3953/14–1 | Fayalitic furnace slag                   | Manganese fayalite, Wüstit, leucite, hercynite                       | XRF, LOM, SEM           |
| MST15  | 15,074–440/1–1   | Goethitic smelting slag                  | Goethite, magnetite, manganese fayalite, quartz, leucite             | XRF, XRD                |
| MST16  | 14,162–17b–1     | Iron bloom                              | Fayalite, ferrite, iron oxide (wüstit?), and further components      | LOM                     |
| MST17  | 22,915–3953/12–1 | Plate slag                              | XRF                                                                   |                          |
| MST18  | 23,704–4772/1–1  | Plate slag                              | XRF                                                                   |                          |
| MST19  | 14,971–208–2     | Plate slag                              | XRF                                                                   |                          |
| MST20  | 23,704–4776/3–1  | Fayalitic plate slag                    | Manganese fayalite, leucite, wüstit, quartz                         | XRF, XRD                |
| MST21  | 23,704–4776/3–2  | Fayalitic and wüstitic plate slag        | Manganese fayalite, wüstit                                          | XRF, XRD                |
| MST22  | 22,903–3940/1–1  | Plate slag                              | XRF                                                                   |                          |
| MST23  | 22,915–3953/15–1 | Fayalitic plate slag                    | Manganese fayalite in 2 generation, leucite, glass                   | XRF, LOM, SEM           |
| MST24  | 15,350–469/3–3   | Plate slag                              | XRF                                                                   |                          |
| MST25  | 15,350–469/3–4   | Plate slag                              | XRF                                                                   |                          |
| MST26  | 15,055–359/2–1   | Plate slag                              | XRF                                                                   |                          |
| MST27  | 15,055–359/2–2   | Plate slag                              | XRF                                                                   |                          |
| MST28  | 15,052–1887–1    | Plate slag                              | XRF                                                                   |                          |
| MST29  | 22,846–3939–1    | Fayalitic plate slag                    | Manganese fayalite in 2 generations, wüstit, ferrous glass          | XRF, LOM, SEM           |
| MST30  | 22,903–3940/1–2  | Running slag                            | XRF                                                                   |                          |
| MST31  | 23,704–4776/3–3  | Running slag                            | XRF                                                                   |                          |
| MST32  | 23,704–4776/3–4  | Fayalitic running slag                   | Manganese fayalite in 2 generations, ferrous and aluminous glass     | XRF, LOM, SEM           |
| MST33  | 15,052–1887–2    | Running slag                            | XRF                                                                   |                          |
| MST34  | 15,074–440/1–2   | Running slag                            | XRF                                                                   |                          |
| MST35  | 23,704–4772/2–3  | Running slag                            | XRF                                                                   |                          |
| MST36  | 23,704–4772/2–4  | Running slag                            | XRF                                                                   |                          |
| MST37  | 15,053–169/2–3   | Running slag                            | XRF                                                                   |                          |
| MST38  | 15,350–469/3–5   | Fayalitic running slag                   | Fayalite, wüstit, ferrous glass                                      | XRF, LOM, SEM           |
| MST39  | 15,350–469/3–6   | Fayalitic and wüstitic running slag      | Wüstit, manganese fayalite                                           | XRF, XRD                |
| MST40  | 15,061–254/2–2   | Running slag                            | XRF                                                                   |                          |
composition and phase assemblages (Tables 2, 3 and 4),
two of them are more likely furnace slags (MST 12; MST 14; Tables 2 and 3),
because of their high contents of minor components like manganese or basic oxides, which should be reduced during the refining process (Serneels and Crew 1997). Therefore, the proportion of smelting slag is slightly higher than assigned only by morphological features.

Only three samples of the ore looking material analysed may be suitable iron ores (MTS 02; MTS 03; MTS 05), with mainly haematite ($\text{Fe}_2\text{O}_3$) and some goethite (Table 4). These three samples are of high grade with minor quantities of clay minerals and sand, but with some percentages of manganese, allowing their use for the bloomery process (Tables 2 and 3). Contents of self-fluxing agents like calcium, potassium, or phosphorous are low. Their high content of pure haematite and their porous state suggests that they were roasted before use. One sample is an aluminous and iron-bearing sandstone (MST 01). Another sample with grey-brown colour (MST 04) looked optically also like an iron-bearing sandstone, but it shows an apatite-like composition with an iron content below 1% (Tables 2 and 3). XRD analysis shows that it contains nearly pure hydroxylapatite (Tables 4), so that one cannot exclude the possibility that it is a bone. Since it is also filler material, it is questionable whether it is related to the iron smelting process or not.

The comparison between the iron contents of slag and ore refuse shows that some slag has higher iron contents than the ore (Fig. 9), which indicates that some ores used for smelting were richer than ore refuse from the excavation, as part of the iron content in the ore has been removed as a metal. The calcium contents of the slag are slightly higher than in the ores, which is due to the enrichment of gangue minerals or the input of the charcoal ash and no indication for flux addition (Fig. 10).

The bloom’s weight today is around 1 kg, because post-excavation corrosion has converted most of the metallic iron into rust compounds that has fallen off during storage. The metallic iron is spongy with fayalite and wüstite slag in between (Fig. 11). The main composition of the adhering slag is identical to some macro slags mentioned before. The iron is entirely ferritic, but shows precipitated carbide or carbo-nitrite needles (Fig. 12).

| Lab no | Find no       | Classification       | Phases                      | Methods     |
|--------|---------------|----------------------|-----------------------------|-------------|
| MST41  | 15,055–359/1–2| Running slag         |                             | XR F        |
| MST42  | 15,055–359/1–3| Fayalitic running slag| Fayalite, wüstit, quartz    | XRF, XRD    |
| MST43  | 22,915–3953/12–2| Running slag        |                             | XR F        |

Fig. 5 Microstructure of a plate slag with fayalite and glass with pores of different sizes
Discussion

As mentioned before, most of the slag materials from both houses have weights less than 100 g, whereas slag blocks from Roman smelting sites can have the several kilogramme weight (Dunikowski and Cabboi 1995; Schrüfer-Kolb 2004). The slags from the houses 3 and 4 have been chopped up to hand samples to make them suitable for fills, together with hand samples of iron ore.

Fig. 6 Microstructure of a running slag with dendrites of wüstite and primary fayalite laths within a matrix of glass and fayalite

Fig. 7 Plate slag with fayalite-leucite eutectic and some hercynite
Fig. 8 Fayalite between wustite-leucite eutectic and some hercynite

Fig. 9 Relationship between ore and smelting slag by typical gangue and “flux” components
Fig. 10  Comparison of ore and smelting slag by barium and lime contents

Fig. 11  Microstructure of the bloom with agglomerated particles of metallic iron within a fayalite-wüstite-glass matrix
and other geological materials. More than 92% of the investigated slag can be assigned to a smelting process, which must have been practised in the immediate vicinity, as it is unlikely that waste products were transported over several kilometres. As mentioned before, some on-site findings show impact of heat and are interpreted as furnaces (Braun 2019). Sunken-floored or sunken hearth furnaces from the early Romano-Barbarian site of Tuklaty in the Czech Republic are slag-pit furnaces, which do not allow continuous removal of the slag (Pleiner and Salac 1987; Pleiner 2000). Running slag and especially plate slag clearly indicate that they derive from a process in slag-tapping furnaces, which is typical for the Roman period (Cleere and Crossley 1995; Dunikowski and Cabboi 1995; Schrüfer-Kolb 2004). The furnace slags would indicate that non-tapping furnaces that do not have a slag evacuation system have been used too, which would be in accordance with sunken hearth furnaces of the Tuklaty type. Indeed, the chemical compositions and phase assemblages of tapped and non-tapped slag do not differ and would imply that the same ore source was used. Furthermore, very similar process conditions must have prevailed. There are therefore various explanations for these contradictory results. The best and simplest explanation is that the furnace slag may derive from an interrupted or incomplete furnace cycle where the right temperature was not reached to make the slag liquid to get tapped. Such furnace slag is regularly found in Roman slag-tapping furnaces in Gaul and Britain (Dunikowski and Cabboi 1995; Sarreste 2014; Schrüfer-Kolb 2004). Another explanation is that they may derive from pre-Roman ancestors. Pre-Roman smelting furnaces were usually non-tapping furnaces (Cleere and Crossley 1995; Dunikowski and Cabboi 1995; Gassmann and Schäfer 2014; Schrüfer-Kolb 2004; Stöllner and Zeiler 2014).

As there are several ore fragments under the filling material in addition to the slag, it is reasonable to assume that they are also connected to the smelting process, especially as some of them had actually been roasted, which would be consistent with the practice of other Roman smelting sites (e.g. Chech 2017; Cleere and Crossley 1995; Schrer-Kolb 2004; Tylecote 1986). Otherwise, it could also represent material discarded as unsuitable. The aim of this study is not linking slag to ore or metal, as trace element and osmium isotope analysis is still in process, but it has been a point of principle to check if all the ore fragments that have been used for filling material can be related to smelting process or not. A simple comparison of main and minor components clearly shows that those haematite ores were suitable to produce such slags. Indeed, the plot of iron against silicon (Fig. 9) clearly shows that some slags have higher iron contents as the ore refuse, found within the houses. Since these are mainly plate slags, there is no reason to assume that they could be smithing slags, but it becomes clear that higher graded ores must have been used than those found within the archaeological context of the houses 3 and 4, analysed here in this study. Such high-grade haematite ores usually contain only minor quantities of gangue, which is needed to form a
slag and must consume furnace lining and ash as a source of alumina and quartz (Crew 2000; Kronz 2000). The addition of low-grade ore like the iron-bearing sandstone from the excavation could also have been an opportunity to add some gangue material to high-grade haematite ores, which will be checked by further analysis (Fig. 10).

Conclusion

The first results of ongoing investigation into metallurgical debris from the vicus of Eisenberg clearly prove the smelting of iron in or in the immediate vicinity of the vicus of Eisenberg during Roman times. All investigated material has been crushed to small pieces with less than 100 g weight, so that none of the slag can obviously be in situ and therefore the dating of the archaeological strata can only give termini ante quem, so that the beginning of the iron smelting must have been before 20 BC. The types of furnaces used for smelting are not clear, as different reconstructions of archaeological record resulted in quite different “types” of furnaces, for which reason it must remain open what kinds of furnaces were actually used. The total volume of slag debris examined from the two houses naturally represents only a tiny section of the large-scale iron production on site, so that no quantitative conclusions can be drawn from it. This is firstly because mainly slag from well stratified and dated features was selected for this study, and secondly because the whole area was levelled around 70 AD, i.e. before the construction of dwelling zones at this site, and much material was moved to other sites and deposited there. Furthermore, slag at Eisenberg was also frequently reduced in size and may have been transported to convenient spots and dumped, but parts of it were crushed and reclaimed for use as filler and road material on the ground.

The compositions of the slag clearly indicate that a deliberate addition of fluxes like limestone was not practised, but the high-grade haematite ore refusives, found within the slag were suitable to produce low viscosity iron oxide rich slag within the range of the silica-fayalite eutectic. Eutectic textures of fayalite, wüstite, and leucite indicate locally lower temperatures, where the additional alkali support may derive from the fuel ash. The ores were obviously roasted, and other ore dressing may have been performed for upgrade, but the low content of gangue is likely to have caused the need for additives like furnace lining or low-grade iron ores to form a fusible slag in sufficient quantity.

Acknowledgements

We are grateful to the Bettina Hünerfauth M.A. from the GDKE in Speyer for her support of handling the corpus of finds and to Dr. Heinrich Taubald from the Department of Geoscience at the University of Tübingen who has performed the WDXRF analyses. We thank two anonymous reviewers for their constructive reviews.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest

The authors declare no competing interests.

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