How did the iron industry change from the Iron Age to Roman Period in Southern Britain?

A study of smelting technology through smelting slag

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Thesis submitted for the degree of D.Phil., Archaeological Science

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Trinity Term 2018

ABSTRACT

This thesis explores the transition between the Iron Age and Roman periods in Britain using one of the most survivable and data packed archaeological artefacts, iron smelting slag. By using a series of complimentary analytical methods it is possible to reconstruct the smelting process. Not just on a purely metallurgical level but also revealing some of the actions of the smelters. The transition from the Iron Age to the Roman period has been a longstanding area of discussion in European archaeology, marking the change from prehistory to protohistory. A geographical limitation has been placed on this study to southern Britain, this is to cover the area with the most complete coverage of archaeological sites and also with a distinct archaeological change between the two periods. The analysis of smelting slag at a macromorphological level reveals furnace morphology and operation. The microstructure of the slag examined using reflective light microscopy reveals under what conditions the slag solidified. The chemical composition of slag determined using Scanning Electron Microscopy Energy Dispersive Spectroscopy (SEM-EDS) reveals the inputs to the smelting process and through their interaction the temperature and chemical change within the furnace. Combining these methods adds further information about the smelt, giving the reasons for the identifiable characteristics of the smelt. Traditional metallurgical analysis of iron smelting slag has focussed on the purely technical result of the smelt, effectively how efficient the smelt was and what ore was being used. The results of this study indicate that the production of iron from the earliest period in Britain was part of a complicated wider picture of resource exploitation, interaction between groups geographically and temporarily.

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ACKNOWLEDGEMENTS

This work would not have been possible without contributions in many forms from many people. My inspiration over the last 10 years and the driving force behind my ambition to get slag recognised for its true worth is Gerry McDonnell. I was fortunate enough to continue to be exposed to slag and given the opportunity to excavate iron smelting sites while employed by Thames Valley Archaeological Services. The practical support of Chris Doherty, discussions with Dr Sarah Paynter of Historic England and Dr Peter Bray and Dr Ruiliang Liu of RLAHA and the supervision of Prof. Mark Pollard and relentless encouragement, proof reading and supervision of Dr Wendy Morrison. I would not have been able to complete this work without samples obtained from Ruth Carter (Beauport Park), Paul Green (Bradenham Bloomery), Mike Charlton (*Ironworks samples* – Shooter's Hill, Lightwater and Stockbury) TVAS, Wiltshire museum and the Dean Heritage centre. Alongside the academic support I have been fortunate enough to receive immense emotional support from family; my parents, my brother Chris and his partner Mel have always been there over the last 3 years. My friends in the lab, Danielle, Elizabeth, Eleanor, Maciej, Paddy and the rest of the DPhil office who were always there to support my caffeine addiction. My college buddies in particular Georgia, CJ, Rory and Bas but also the rest of the MCR who were subjected to an evening tirade or two and responded with pango soaked understanding and Hertford College Boat Club for providing me with a route to vent frustrations through healthy and not so healthy activities and a passion and group of friends who will remain with me throughout. I cannot express how much I am grateful to have been supported throughout my studies by my soon to be wife Sara, without her continual encouragement, love and assertion that I would be able to finish I would never have been able to complete this thesis in any sort of timely manner.

CHAPTER 1 - INTRODUCTION

1.1 THE STATE OF PLAY

The transitions between archaeological periods, notional and problematic boundaries at best, are generally poorly understood. Assigning pre-determined labels (e.g Bronze Age, Iron Age etc) to temporal divisions can isolate period-based specialists and limit their focus. These specialisms can then halt at a point in time decided through modern eyes. As an occupation, it could be argued that the transition between the Iron Age and Roman period could be one of the less obscured transitions. However, it is more complicated than an occupation starting in AD 43 (Webster 2001, 209). The transition between the Iron Age and the Roman period has been widely discussed with the accepted wisdom changing from one of an invasion and occupation to early contact and interaction (Morrison 2015, 17). The archaeological evidence supports the existence of lines of communication and trade between Britain and continental Europe and the Roman empire long before the legions appeared on the south coast of Britain (Morrison 2015, 14).

Initially, iron usage was more prestigious than utilitarian, being used for high status objects such as weapons and horse trappings later becoming used for ubiquitous tools and fittings (Pleiner 2000, 32). This means it is very well placed to be able to contribute to the answering of archaeological questions. However, archaeologically speaking, iron is a difficult material. It does not survive well in most burial conditions, and, being used to make every-day utilitarian objects, it is not considered exciting in most contexts (McDonnell 1986). Overwhelmingly used for nails and pragmatic tools, iron does not inspire the same passion and intrigue that other materials, even other metals can. These factors mean that although it is widely accepted to be a key material in later human history, it is still comparatively poorly understood.

There have been two main methods of historic iron production; the bloomery process and the blast furnace. The bloomery process dominated the production of iron in Britain until the 15th century before being slowly superseded by the blast furnace (Bayley *et al.* 2001, 4; Dungworth 2015, 24). These processes are referred to as the direct and indirect processes respectively. The direct process produced in a single process iron which was forgeable while the indirect process produced cast iron which would require further processing to transform it into a forgeable metal (Pleiner, 2000 131). These terms are not to be confused with modern metallurgical terms which refer to the method of reduction not the production of forgeable metal (Bodsworth, 1988, Clough, 1987).

1.2 Thesis Aims and Objectives

How did the iron industry in Southern Britain change from the Iron Age to the Roman period?

To be able to answer this overarching question it will be necessary to understand not only *how* iron was produced but also the cultural setting in which this took place therefore these aims need to be accomplished.

These broad aims are to:

- establish the archaeological and technical background of iron and iron smelting in Iron Age and Roman Britain.

- use this background information to compare the smelting process in the Iron Age and Roman periods.

To complete this first aim it is necessary to complete the following objectives:

- The ancient iron smelting process and the role of slag within this process must be understood. This will be through a review of the current understanding and literature of bloomery iron smelting.
- It is necessary to understand the Iron Age and Roman periods in Britain and the position of iron within them. This will also be achieved through a review of the literature regarding research into the Iron Age and Roman periods.

Both of these objectives will be combined as a chapter reviewing existing research.

The second aim will be completed through the following objectives.

- Assemblages of smelting slag will be identified and sampled for analysis.
- These samples of slag will be analysed using a holistic analytical method to reconstruct the smelting process.
- Combine these results with the archaeological information for each period
- Using the trends and individual features to compare the two time spans covered in this thesis.

1.3 SCALE OF THE PROJECT

1.3.1 Temporal Scale

This thesis looks at the transition between the Iron Age and Roman periods in southern Britain; therefore, it is necessary to look at sites from across this timespan. However, as discussed later, the dating of many of these sites is problematic. An ideal situation would be to study sites that are tightly dated to immediately before and after the arrival of and occupation by the Romans. Frustratingly, limitations imposed by dating techniques mean that this is not possible and thus a wider temporal range is necessary to give a more complete picture. The Iron Age within Southern Britain begins around 800BC (Cunliffe 2005, 88). Iron smelting has so far been identified as arriving later as a complete package having been developed elsewhere (McDonnell 1986, 86). This does not mean that there was no modification of the process or independent innovations once it had arrived. It can be argued that despite the successful invasion in 43AD the Roman Empire had already influenced the Iron Age communities of the South of Britain substantially. Equally there were regions which although inevitably influenced by having the Romans as a next door neighbour they did not adopt Roman ways and methods (Morrison 2015, 7). For the purpose of this thesis, samples have been selected from the Early Iron Age (700BC) through to the Late 2nd Century AD.

1.3.2 Spatial Scale

The spatial scale of this thesis is a key consideration for two main reasons. From a metallurgical standpoint, locations where iron ore is available in a form which can be smelted using ancient methods are limited. From an archaeological standpoint, the different cultural groups present across Britain during the iron age may have had very different cultural needs and norms.

The distribution of iron ores across Britain is not as restricted as other metallic ores such as copper, lead or tin (Figures 1 and 2). There are deposits of exploitable iron ore across much of the country with only the chalk uplands of the south of Britain having deposits of ore which were not able to be processed. As well as the geological sources of ore there are also bog ore deposits (Bayley *et al* 2008, 5). These are formed in wet areas by the dissolution of dissolved iron oxide. This type of ore can be more widespread than geological ore sources and it also is more easily recovered. The different sources of ore will have different amounts of accessible iron oxide and different types and amounts of impurities which will all affect the smelting process. The distribution of different ore bodies is important to know to understand the composition of the slag (Charlton *et al* 2013, 425).

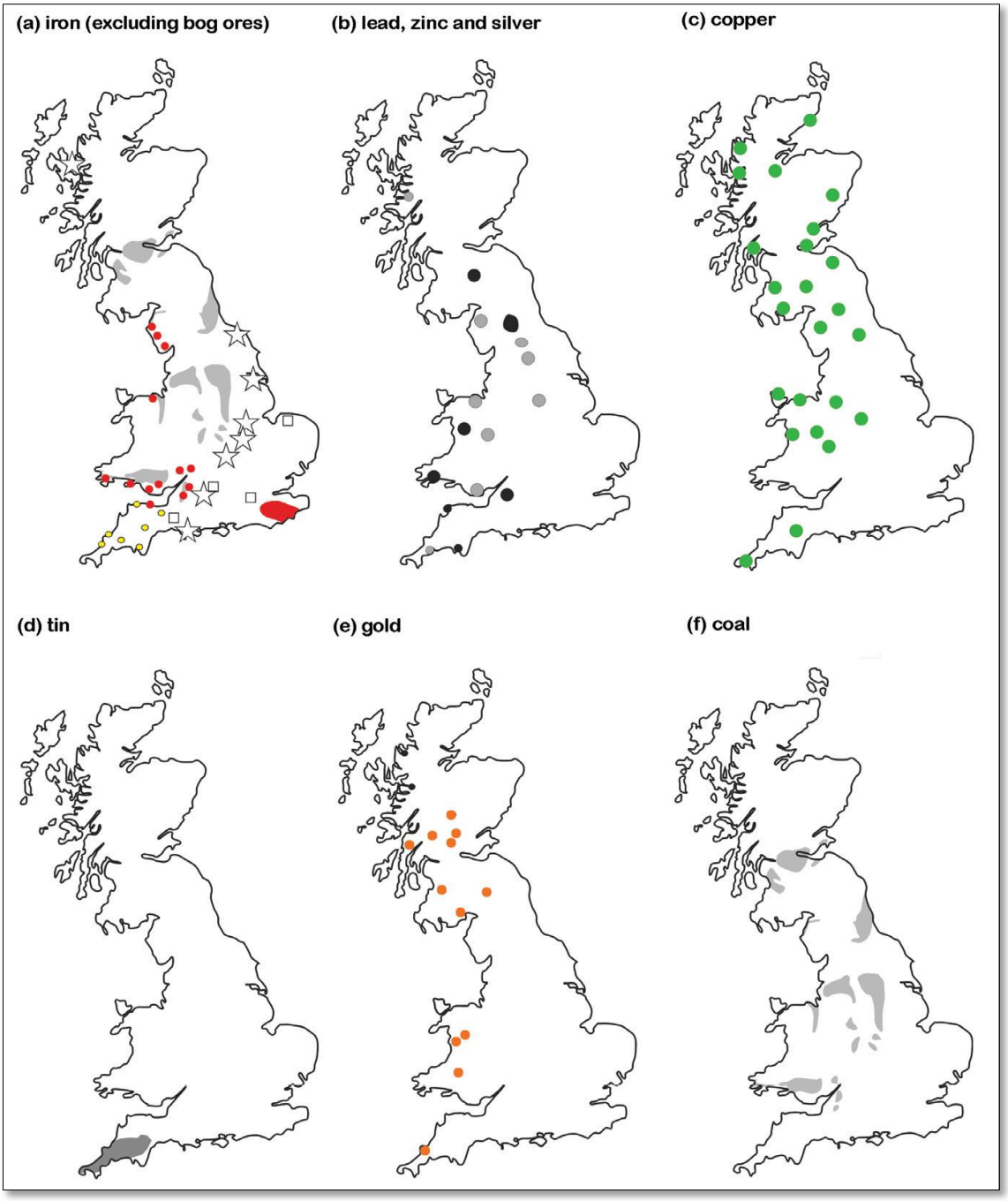

Figure 1 Distribution of metallic ores and geological fuels in Britain (from Bayley et al 2008, 5) a) Iron: (excluding bog ores): grey tone + the carboniferous coalfields with claystone and blackband sedimentary ironstones; red = the weald, cretaceous claystone ironstones; yellow spots = oxide iron ores associated with the SW mineral province, including gossan and oxides after siderite; red spots oxide iron ores associated with epigenetic mineralization on mesozoic basin margins; stars = sedimentary ooidal ironstones of mesozoic age; squares = other sedimentary ironstones of mesozoic-tertiary age b) Lead, Zinc and silver, areas indicate main lead-zinc orefields, those in black produced significant quantities of silver, c) copper, d) tin: working of alluvial tin deposits in SW England took place over a wider area than the distribution of the primary mineralization, e) gold, f) coal

Figure 2, Metallic ores exploited during the Roman Period (based on Jones and Mattingly 2002)

The archaeological scale of the project is very important. There is strong archaeological evidence for different archaeological cultures across Britain during the Iron Age (Hill 2011, 266). How these cultures used and viewed iron may be important factors into how they produced it. The impact of the Roman Empire was not the same over the whole of Britain. Although they did move into Northern Britain they did not maintain the same level of influence over the more northern regions as they did across the south of Britain. Possibly the most influential factor from the archaeological scale of the project is the density of

archaeological research across Britain. It could be said that there has been a stronger tradition of archaeological research in southern Britain compared to northern Britain; certainly, some areas of Britain have been studied in more detail with regards to identifying iron smelting activity (Figure 3) (Darvil and Russell 2002, 22).

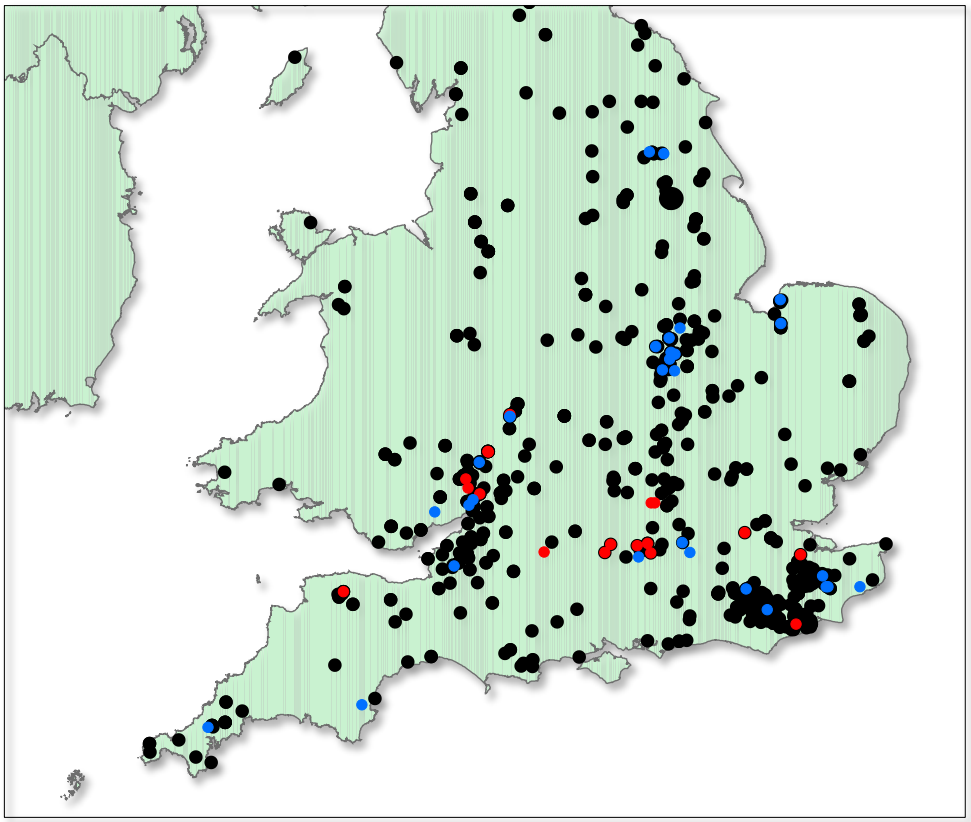

Figure 3, Iron Age and Roman iron smelting sites in Southern Britain: Red = sites examined in this thesis, Blue = sites with existing published slag analyses, Black = sites recorded as having 'Iron Smelting' or 'Bloomery' in online databases described later

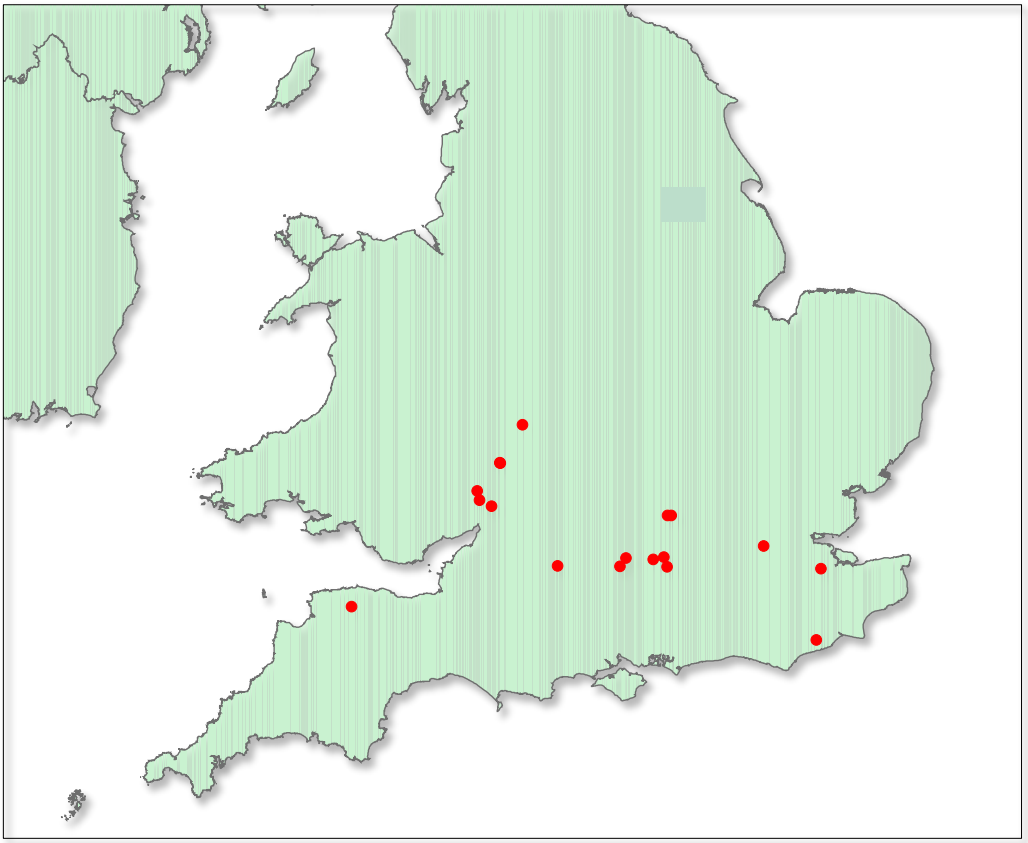

Figure 4, Location of sites studied in this thesis

1.4 Structure of the Thesis

This thesis is divided into five chapters each of which has further sub divisions. Having already outlined the major aims, how I will be approaching it and why I have limited the scope of the work. Chapter Two then delves into the literature concerned with the processes of making iron, the understanding of slag and the archaeological setting of the periods. This includes the science of smelting iron through the chemistry and ores, furnace types and furniture and finally interrogating our definitions of slag. It then reviews what work has previously been carried out to understand iron slag, firstly as a generic exploration of the material and processes involved with its production, before moving on to look more specifically at the periods and regions pertaining to this thesis. The archaeological understanding of iron production and the role and importance of this most functional of metals in the periods studied here will be critiqued to frame the results produced here. Chapter three describes the sources of information, the sites and the methods employed throughout this study. The biases inherent in and introduced into the samples during the project are also described and discussed. Each of the different sources of data used to identify, select and provide the archaeological background. The samples have inherent biases resulting from their origins and further biases will be introduced at each stage of analysis. The process of sample selection has to vary for the different assemblages therefore these selection criteria are laid out. Once the samples are selected they will be analysed macromorphologically, micromorphologically and chemically. How each of these methods will be employed will be described before these methods are used to analyse the selected samples. The sequential analysis of the samples from each site will be described in chapter four. The macromorphological and micromorphological analyses combine to describe the life history of the slag, this is used to choose which samples will be analysed chemically. The chemical analyses will be used to calculate the

properties of the slag. Results from each of the sites will be used to describe how the smelting occurred on each site. The results will be compared and contrasted both spatially and chronologically within the samples of this study. Chapter five will compare these new results to the current archaeological and archaeometallurgical thoughts to understand how the production of iron changed from the Iron Age to the Roman period in Southern Britain.

The archaeometallurgical thoughts of how iron was produced and the role of iron and iron production in the Iron Age and Roman periods are described in the following chapters.

CHAPTER 2 – MAKING IRON AND UNDERSTANDING SLAG

2.1 THE SCIENCE OF SMELTING IRON: PROCESS AND RAW MATERIALS

2.1.1 Chemistry

The process of reducing iron from its ore, or smelting, has been extensively discussed (Pleiner 2000; Buchwald 2005; Rostoker and Bronson 1990; Tylecote 1990) however the direct process (i.e bloomery smelting) is still not fully understood despite the level of study into it. Three strands of research can be identified, analytical, experimental and ethnographic. Analytical work has focussed on understanding the iron smelting process purely from a technical point of view, often ignoring the human factor in the smelting process. Experimental work has been focussed on producing iron, often this has been the only focus to the detriment of replicating the archaeological remains or testing a technical theory. Ethnographic research has successfully recorded the human factor, it is limited by the replacement of local traditional methods being replaced by imported materials.

The understanding of how iron was produced is considered by the author to be best approached by a combination of the experimental and analytical methods. Analytical methods have proposed methods by which the process could work theoretically, while experimental smelting has confirmed or denied many of these theories. The following description is led by analytical work but where experimental work has identified that the theory may not apply this is discussed.

The underlying principle of the extraction of iron is the chemical reduction of iron oxides (FeOx) into metallic iron (Fe(m)) (Pleiner 2000, 131), changing the brittle, friable, and almost useless iron ore into the strong, malleable metal. Iron oxide (FeOx) can be reduced by carbon monoxide (CO) at temperature of around 800°C (Tylecote 1990, 73). This is

significantly below the melting temperature of pure iron (1535°C) (Scott 2014, 4; Weast 1985; Samuels 1980, 42).

The understanding of the smelting process in the ancient world cannot be considered purely from a modern metallurgical view (Hingley 1997, 9). Iron smelting was understood and replicated in a different frame of reference than that of modern science. Therefore to illustrate this the idea of a typical smelting event will be used to describe the understanding of the iron smelting process as it currently stands.

A furnace has been built measuring about 1m high and 0.35-0.4m in diameter. The structure has been dried out and fired, the walls are still warm but the furnace still needs to be preheated. The furnace is packed with a charge of only charcoal and bellows are used to raise the temperature. The flames produced from the top of the furnace begin to change colour from a dull reddish colour through orange to a blue almost clear flame as the temperature increases and carbon monoxide begins to be produced. At this stage the production cycle commences with alternating layers of charcoal and ore being loaded into the top of the furnace. Both were prepared in advance being broken up or crushed to a similar size. The bellows are worked harder to increase the temperature through the shaft. As the charcoal begins to burn down the cold iron ore is heated by the rising hot gases, this process brings the ore into the reducing conditions within the furnace. The ore is reduced further as it descends, once it reaches the higher temperatures in the lower regions of the shaft the reduction processes forms metallic iron and the slag begins to be formed. The still pasty slag is heated further and drops down through the region of highest temperature. As it does so, the metal begins to coalesce, forming the bloom. Depending on the type of furnace, the process will differ from this point onwards. In a non-tapping furnace, slag will collect until either enough metal is produced or the airflow is obstructed. At this point, the smelt would have to be stopped and the bloom removed. In a furnace where the slag was

tapped, the slag also builds up at the base of the furnace to the point of impeding airflow, but if this happened, the slag would be drained from the furnace. The slag would be tapped out regularly to allow for the smelt to continue uninterrupted.

The initial drying of the furnace increases the strength of the furnace (Sauder 2013, 70). Experimental work (Sauder '*Bloomery Construction'*, 12) has shown that a poorly prepared furnace can crack at high temperatures causing a decrease in temperature and a change in the redox conditions. In theory the preheating of the furnace allows for the charge to be more easily heated to reaction temperature (Cavallini 2013, 1051). Sauder ('Update on the "Practical Treatise", 2) has shown that it actually may be a waste of fuel to try and preheat the furnace as the most efficient way they have found to do this is by forming the liquid bath of slag by charging ore and fuel together.

The work of Crew (1991; 2013; Serneels and Crew 1993) has shown that the proportions of fuel to ore is an important variable in the outcome of the smelt. It has been shown that different raw materials and weather conditions required different proportions of fuel and ore to be used (Crew 2013, 43; McDonnell 2013, 62-63). Therefore this would be a highly variable aspect of the smelting 'recipe'.

The reduction of iron oxides (FeOx) by CO is the principal process involved in the smelting of iron, it would have operated in all types of furnace to reduce the FeOx to metallic iron (Fe(m)) (McDonnell 1986, 22). Carbon monoxide (CO) is crucial as the main reduction agent in the direct iron smelting process. Oxygen (O) combines with carbon (C) from the charcoal to form CO_2 ($2C + O_2 \rightarrow CO_2$) then subsequently CO ($CO_2 + C \rightarrow 2CO$) (Pleiner 2000, 133; Charlton 2007, 89). Theoretically the production of CO would increase, making the conditions in the furnace more reducing until it reached a level at which the FeOx would be reduced to Fe(m) (Cavallini 2013, 1050). The CO

flows through pores in the ore and reduces the FeOx via the following sequence of reactions (Charlton 2007, 89):

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$

$$FeO + CO \rightarrow Fe + CO_2$$

These reactions require significant quantities of heat to drive them to completion (Charlton 2007, 90). The temperature inside a typical furnace would have to be raised to 1200°C – 1400°C in the combustion zone (Bachmann 1982, 10; Tylecote 1987, 129). This zone would have had an oxygen content too high for reduction to have taken place, just above this zone reducing conditions would have been much greater, in the reduction zone (Charlton 2007, 90). It is possible for the direct reduction of FeOx by solid C if the temperature is over 800°C, this is not the predominant reduction reaction but it may have an important role in the initiating bloom formation (Charlton 2007, 90).

The formation of a bloom is by small particles of Fe(m) becoming sintered together, forming the entangled network known as a bloom. It has been shown in experiments and ethnographic reconstructions to form on the furnace wall just below the tuyère (Charlton 2007, 91) although it has been shown to form away the wall in a bath of slag (Sauder and Williams 2002, 124). There are two mechanisms proposed for the formation of the bloom; the accumulation of solid formed iron grains as described above, and the production of liquid cast iron which collects in the combustion zone where it is decarburised and solidifies. Gordon and Killick (1992, 160) in their study of the American bloomery process suggest that a number of different processes combined for the former; the direct reduction of magnetite grains and mechanical agglomeration,

indirect reduction of excess iron oxide dissolved in the slag. The precipitation of iron around charcoal particle serving as nucleation points for directly reduced ore grains was proposed as the start of the bloom formation process (Gordon and Killick 1992, 160; Charlton 2007, 91-92). The evidence for the latter method is in the form of small cast iron spheres (David *et al* 1989, 196; Pleiner 2000, 132). Whether there is enough evidence to suggest either of these was a normal mode or simply localised extremes is unclear (Charlton 2007, 92). Nevertheless the bloom formation processes are always benefitted by the production of a fluid slag.

Iron ore is never formed of pure iron minerals, containing different amounts of unwanted minerals, known as the gangue. These must be removed from the metal either by mechanical processing, thermo-chemically as a gas or by dissolving in a liquid slag (Charlton 2007, 92). The main gangue element is silica which has a melting temperature of 1723°C; significantly above furnace operating temperatures. Therefore to melt it would requiring fluxing with other materials to produce a phase with a lower melting temperature. Iron oxide fluxes silica to form the mineral phase fayalite (Fe_2SiO_4), it has a melting temperature in the same range as the bloomery smelting furnace and has a relatively low viscosity relative to temperature (Charlton 2007, 93; Rehren *et al* 2007, 212-214). These fortunate properties make this phase ideally placed as the base for a liquid slag. Manganese Oxide (MnO) and lime (CaO) are also common in iron ores and can flux silica taking the place of iron oxide. Most iron ores are self-fluxing and do not require further additions to create a fluid slag (Craddock 1995, 244). Other constituents of ores include alumina (Al_2O_3), phosphorus oxide (P_2O_5) and titanium oxide (TiO_2), these are also removed in the slag. Phosphorus oxide is also volatilised into the atmosphere and becomes incorporated into the metal. Phosphorus is alongside carbon as an important alloying element for iron in the bloomery process (Godfrey 2007, 23).

Melting furnace walls, tuyères and fuel ash would also be dissolved into the slag (Craddock 1995, 146).

The most desirable property of an iron smelting slag is low viscosity, it is much easier for iron particles to come together in a free-flowing slag and it is much easier to separate a free flowing slag from the bloom of iron (Charlton 2007, 93).

Once it has been formed the liquid slag transports and collects solid iron particles to form a bloom, it acts as a heat reservoir and protects the iron from oxidation when it enters the combustion zone (Charlton 2007, 94; Sauder and Williams 2002, 128). Rather than being an inefficient consumption of iron, slag production is an indispensable part of the bloomery process.

As a smelt progresses, the slag is allowed to collect at the base of the furnace, drained into a pit beneath the furnace or removed from the furnace by raking or tapping (Craddock 1995, 244; Bayley *et al* 2001, 11). If the slag is removed from the furnace by tapping or by draining into a pit beneath the furnace then the smelt can be continued and a larger, cleaner bloom of iron can be produced (Craddock 1995, 245-246; Charlton 2007, 95). The smelt is ended by either the removal of the bloom or the conditions in the furnace causing bloom formation to halt.

An important factor in the chemical processes of the smelt was the operating temperature. This would have affected the production of reduction gases, the creation of metallic iron and slag, the liquidity of the slag, and its separation from the bloom. It is therefore necessary to be able to estimate the temperature in front of the tuyere (Morton and Wingrove 1970). The temperature at which the direct smelting process was thought to be carried out has been widely discussed, with several temperature ranges having been suggested (Tylecote and Wynne 1958; Pleiner 2000; Mack et al 2000; Clough 1987). The melting temperatures of most bloomery smelting slags are in the region of 1100-1250°C,

however to ensure the slag is fully liquid outside the hottest part of the furnace then the furnace would be operating at a higher temperature (Morton and Wingrove 1970). These temperatures were initially estimated based on the temperatures at which iron could be reduced (Percy 1864) once it was realised that the process required the formation of a liquid slag the liquidus temperature of this was used (Tylecote 1990, 130). However, with experimental archaeological smelts being carried out the true temperatures attainable in the furnace were realised as well as the need to have a raised temperature to keep the slag liquid (McDonnell 2013). When the consideration of the viscosity of the melt is also brought in then a higher temperature may also have been required (Kresten 1986; Freestone 1988). Several variables in the composition of smelting slag can increase the viscosity, possibly the most important is free iron oxide. By increasing the amount of free iron oxide in the slag, it is possible to decrease the viscosity; however, it also decreases the amount of iron oxide available to reduce into metallic iron. Nonetheless, by doing this, the melting temperature of the slag is raised, albeit to a lesser extent than the effect that the iron oxide exerts on the viscosity.

It is impossible to deny that the bloomery process was less efficient than a cast iron system as so much iron was lost to the slag. It is possible to estimate this efficiency by quantifying the iron present in the ore and slag, when both are available. The effective ore quality would be dampened if the slag contained significant contribution from the furnace wall or fuel ash (Charlton 2007, 94).

2.1.2 Ore

Iron ores are more widely available than other metallic ores, as it is possible for iron ores to be created in more geological formations than the non-ferrous metal ores. Even though iron is one of the most common elements in the earth's crust it is only in the right

composition and concentration that it can be classified as ore. The frequency and identification of ores was described by classical authors (Pliny, book 34, XLI):

'Deposits of iron are found almost everywhere.... Very little difficulty in finding them as they are indicated by the actual colour of the earth'

There are four types of geological iron ores present in Britain: magnetite, hematite, hydrated ores, and carbonate ores (Cleere 1981, 53-54); of these only hydrated ores and carbonate ores were commonly exploited. The most heavily studied areas archaeologically have been the Weald of Sussex and Kent (siderite and limonite ores), the Forest of Dean of Gloucestershire (limonite and some hematite) and the Jurassic Ridge extended from North Oxfordshire through Northamptonshire into Lincolnshire (carbonate ores). These larger deposits have been studied for commercial exploitation, and information on them is available from geological surveys (Groves 1952). Smaller deposits of iron ore were also available across much of the rest of the country. As these were not commercially exploitable, they were often understudied. Some information on the composition of these is available from ore samples found on archaeological sites (Paynter 2006; 2007; Young 2010). There are also a series of tertiary ore deposits across Britain, formed by precipitation and in-situ growth of iron minerals within the overburden (Young 2010, 1). Bog ore is formed as a precipitate in wet marshland conditions and is commonly found where iron precipitates meet either an impenetrable layer or organic material. In these conditions, the iron oxides can be precipitated in layers up to 5-10cm thick over a period of 30 years (Tylecote 1990, 125).

The archaeological evidence for the extraction of ore is not widespread and, in any case, can be difficult to date when it *is* found. Most evidence for the extraction of ore has been quarry pits, such as the exploitation of the nodular ore in the Weald, which was close to

the surface and thus, easily accessible (Pleiner 2000, 92; Cleere 1981, 61). The bedded ores in the Forest of Dean and the Jurassic Ridge form surface outcrops, where they can be excavated easily. There is very limited evidence for subterranean iron ore extraction in Britain during the Roman period and no evidence from the Iron Age. The only confirmed Roman attempt to follow an ore body underground was identified at Lydney Park in Gloucestershire (Cleere 1981, 31). The extraction of bog ore would leave no evidence in the archaeological record as it can be collected by hand from within the wetland where it formed.

The ore can be prepared in a number of ways to increase the richness and also increase the surface area and improve the penetration of the reducing gases (Pleiner 2000, 106-9). Crushing increases the surface area and allows for the washing and/or sorting of the ore. This can separate the iron rich portion of the ore from the mineralogically separate gangue element. The surface area and porosity of the ore can be increased by roasting the ore, as the fractures caused by the heating give the CO more opportunity to penetrate the ore. Roasting also drives off any excess and chemically bound water, which would otherwise draw energy from the smelt (Charlton *et al.* 2010, 353). The excess water would begin to dissipate at 105°C and the chemically bound water would be driven off up to 550°C. As well as these hydrates, any carbonates would be dissociated up to 750°C (Clough 1987; Pleiner 2000, 108). For non-oxide ores they can also be transformed into oxides, which are most suitable for the direct process (*ibid*., 107). This is especially the case for the carbonate ores such as siderite ($FeCO_3$); when roasted in an open fire the oxygen present would oxidise this to magnetite (Fe_3O_4). The oxide forms of ore do not need roasting to alter their composition in order to be smelted. If they were loaded into the furnace unroasted, they would effectively *be* roasted in the upper areas of a shaft furnace, creating fractures and increasing the surface area (*ibid.*, 108). Archaeologically, it can be very difficult to identify

ore roasting sites; unless the same location was used repeatedly, the roasting ore on the ground surface would leave very little trace. It is possible that ore left unsmelted, and thus recoverable from an archaeological site, is not what would have actually been selected for use anyway. The richest ores would have been beneficially smelted therefore the ore left on the site would be the leaner material, rejected by the practitioners.

The furnace would have been 'charged' or loaded with a combination of fuel and ore. The ratio of fuel to ore has been tested thoroughly in experimental reconstructions. Ratios ranging from 1:1 to 3:1 charcoal to ore ratio have been shown to be successful (Bray 2006, 175). The variability of different ores and even different types of charcoal are all 'fixed' variables, set at the start of the smelting activity while the volume of air forced into the furnace and the ratio of ore to fuel being true variables. The control of these modifiable factors is crucial for accommodating different quality ores and to produce different final products.

2.1.3 Charcoal

Charcoal is the main fuel choice for metal production in Britain until the development of the coke fuelled blast furnace in the early 18th century (Pleiner 2000, 115). Charcoal is a more efficient fuel than wood alone and doesn't have the sulphur content of coal, which is detrimental to the production of good iron. Transforming wood into charcoal removes the majority of the water, which means that it burns hotter and more completely than raw wood. Therefore, the production of iron using the bloomery process necessitates the consumption of tree mass (Iles 2016, 1221). Charcoal is produced by burning wood slowly in an oxygen deprived atmosphere, which releases water and other volatile substances. The historic method of producing charcoal was to conduct this slow burn either by stacking wood in a pit or on the ground surface, and then covering (usually with soil) to create the

low airflow atmosphere required (Pleiner 2000, 119-120). Key to the production of iron is a regular and reliable supply of charcoal, which could present a challenge in some regions where there may have been other consumers of charcoal and wood resources (Iles 2016, 1222).

The collection of wood to be converted into charcoal is also a factor to be considered, as certain sizes of wood and possibly different types of wood may have been preferred for the production of iron. Experimental smelts using different sizes and types of wood have confirmed this selective usage was beneficial to the success of the smelt. To have a reliable source of wood, medieval ironmakers would rely on managed woodland, coppiced, or pollarded trees to produce consistently-sized branch wood, which could be easily transformed into charcoal of the desired size for successful smelting. The volume of wood required to produce iron at an intensive level has been suggested to only be possible with managed woodland. The work of Crew and Mighall (2013) has shown that it was possible to run an intensive, if albeit non-industrial, scale smelting site through natural regeneration of surrounding woodland. The smelting activity at Llwyn Du, a 14th century AD smelting site, used mainly oak charcoal with increasing amounts of birch towards the end of each phase of activity on site. This is taken to be evidence for the oak supply running low and birch taking its place (Crew and Mighall 2013, 476-7).

The location of iron smelting sites for fuel, rather than any other raw material, has been established (Sim and Ridge 2002, 37; McDonnell 1986, 20-21) and there is evidence for the abandonment of sites due to apparent exhaustion of fuel (Cleere 1981, 66). Localised industrial processes can lead to the rapid overexploitation of local charcoal resources (Iles 2016, 1222). The Weald, the Forest of Dean and the Jurassic Ridge of Northamptonshire benefited from the combination of ore and fuel in close proximity, which allowed for intensive iron production. There is a growing body of evidence to suggest that Britain was

mostly cleared before the Iron Age (Robinson 1984 for Wessex; Thomas *et al.* in prep for the Thames Valley). However there would have been isolated patches of dense woodland across Britain during the Iron Age and Roman periods and widespread but isolated deposits of iron ore across Britain, but it would be the combination of these two which would dictate the location of successful iron smelting.

The overexploitation of wood resources by industrial scale metalworking has been identified since Theophrastus and Herodotus in the 1st millennium BC (Hughes 1983; Iles 2016, 1224). The connection between iron smelting and charcoal production was summed up by the *Journal of United States Association of Charcoal Iron Workers*:

'We are really the only trade organisation whose interest it is to encourage the growth of forests' (Coffin 1880, 33).

Iron smelters would not have been able to function without healthy woodland to produce the branch wood ideal for charcoaling. A forest may not be entirely depleted but may not be suitable to produce charcoal (Iles 2016, 1225).

The impact of iron smelting on woodland is hard to estimate because there are a number of variables from the amount of wood per unit of woodland to the amount of charcoal produced from raw wood and the ratio of charcoal to ore in the furnace charge. The estimations of how much charcoal can be produced from wood can vary considerably, 100kg of dry oak can give between 12 and 25kg of charcoal (Iles 2016, 1228). The growth patterns of woodland can be difficult to predict as they are dependent on several independent factors (*ibid.*). The amount of charcoal required for a smelt has been calculated from experimental and ethnographic data (Tylecote *et al.* 1977; Crew 1991) but these works have calculated the amount of charcoal in relation to the amount of ore (Iles 2016, 1227). The amount of slag present on an archaeological site is the best measure of the scale

of production, but this is often not measured on experimental or ethnographic iron smelts (*ibid.*, 1228). Where recorded from ethnographic sources, the fuel consumption in relation the ore consumed can vary from a fuel/ore ratio of 1:1 to 4.5:1 (David *et al.* 1989) or 6:1 (Humphris 2010) in forced draught furnaces and even higher (19:1) in natural draft furnaces (Van der Merwe and Avery 1987). Experimental work led by Peter Crew has shown that the fuel consumption can vary between smelt to smelt based on how the furnace was built and operated and the grade of the ore used (Crew 1991; Crew and Charlton 2007; Crew 2013).

The chemical and thermodynamic processes required for a successful smelt fall within a narrow window, yet variations within this have to be made to accommodate different ores and to produce different products. It is therefore quite common for smelting processes to be widely varied in diverse locations across temporal periods. This is especially the case with ethnographic examples, which show great variation in the details of the furnace operation, but most clearly in the furnace design and furnace furniture.

2.1.4 Furnace types

The furnace type and how it was operated are crucial factors in how iron was produced. These factors are not always the easiest to discover from archaeological sites. Furnaces are generally constructed predominantly of clay; in later periods, these are sometimes reinforced with stone or brick. Fired clay is not generally durable enough to survive the burial environment, particularly in conditions generally experienced in Britain or where post-depositional ploughing has occurred.

The size and height of furnace are key factors in determining the conditions which are possible within. Typologies of iron smelting furnaces were originally based on the form of the furnace structure (Percy 1864; Forbes 1964; Schubert 1958) later they were defined by

more functional factors such as slag removal, method of draught and the thermal properties of the walls. It is necessary to limit most of these typologies to geographical regions. There have been a series of furnace typologies based on the furnaces found in the British archaeological record. Cleere (1981) and Tylecote (1990) have both relied on British examples, while Pleiner (2000) looks at a wider range of sites from across Europe.

Cleere (1981, 154-160) focusses on sites in the Weald of Sussex and Kent for these he used a typology split into two groups: non-slag tapping (group A) and slag tapping (group B). There is further definition within these groups as shown in the table below.

Cleere's typology	Diagnostic Features	Subgroup	Characteristics
Group A	**· no provision for tapping of molten slag · hearth below surface of surrounding ground · blown by forced draught**	**A1**	**no superstructure (bowl furnace)**
		A2	**superstructure is a cylinder or truncated cone**
Group B	**· provision for tapping of molten slag · hearth level with surface of surrounding ground · superstructure present**	**B1.i**	**blown with forced draught and cylindrical superstructure**
		B.1.ii	**blown with forced draught and conical or hemispherical superstructure**
		B.2.i	**blown with natural draught and cylindrical superstructure**
		B.2.ii	**blown with natural draught and conical or hemispherical superstructure**

Table 1 Cleere's Furnace Typology

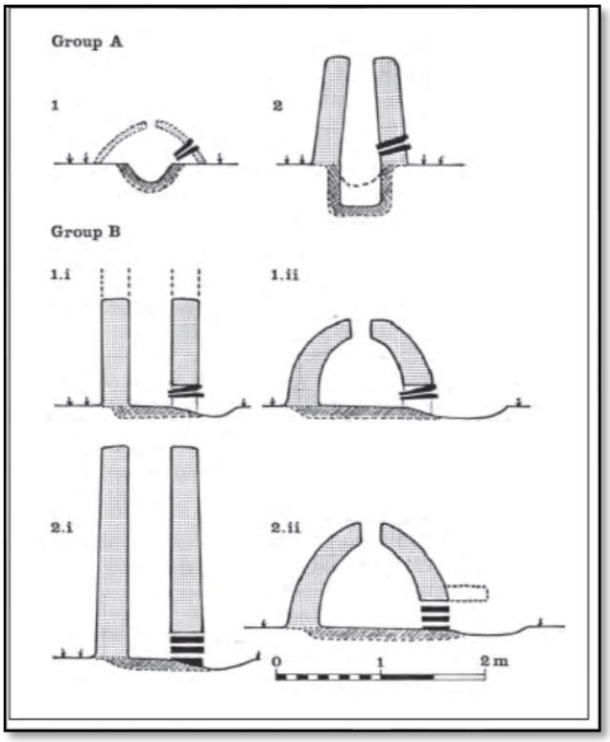

Figure 5, Cleere's furnace types

Tylecote (1990, 132-136) built a typology of furnace types based on furnaces recovered from archaeological research from Europe and ethnographical research from Africa. The first of his types was the bowl furnace and whilst there is not a given definition for this type, the height is roughly the same as the width. Tylecote recognises three subtypes within this[1]:

1. The ore and fuel largely separated with the fuel on the tuyere side, leading to a blast of carbon monoxide through the stacked ore; this is essentially the 'Catalan method'.

2. The same form of furnace but with the fuel and ore layered or mixed rather than being separated completely. These two would be very similar archaeologically but it is generally considered that the Catalan method does not feature in the British archaeological record.

[1] All of these methods are difficult to confirm based on the archaeological record.

3. The manipulated bowl furnace, a furnace based on ethnographic observations. Fragments of iron would have been removed as they were formed, requiring an open bowl with a flared opening.

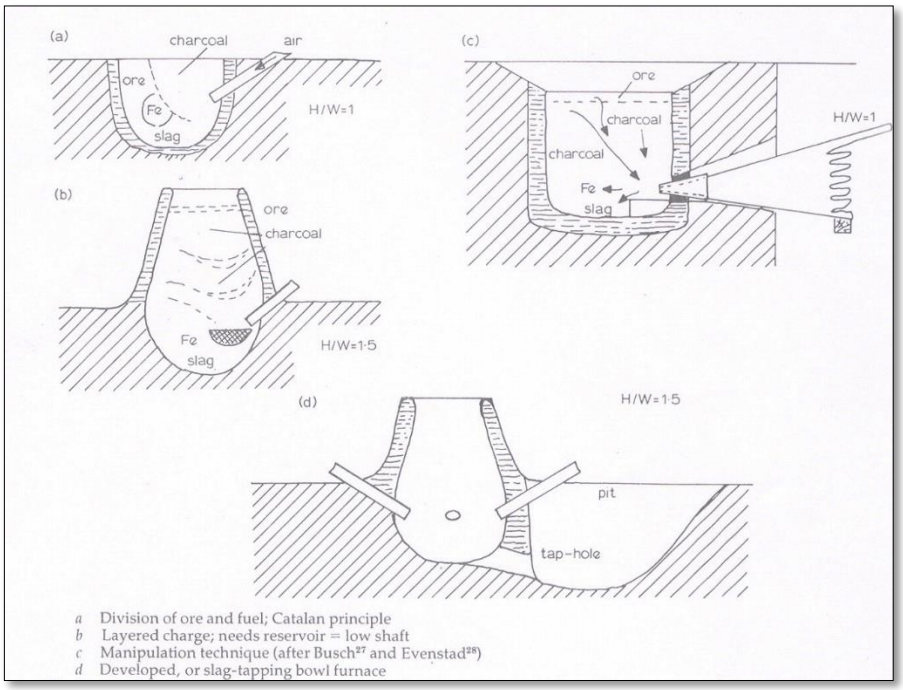

Figure 6, Tylecote's bowl furnace types

Tylecote then refers to the shaft furnace as a second type with the definition being height being greater than twice the width. Two forms of this furnace are discussed, embanked and freestanding, embanked being built into a bank of earth increasing the thermal efficiency and freestanding being built separately.

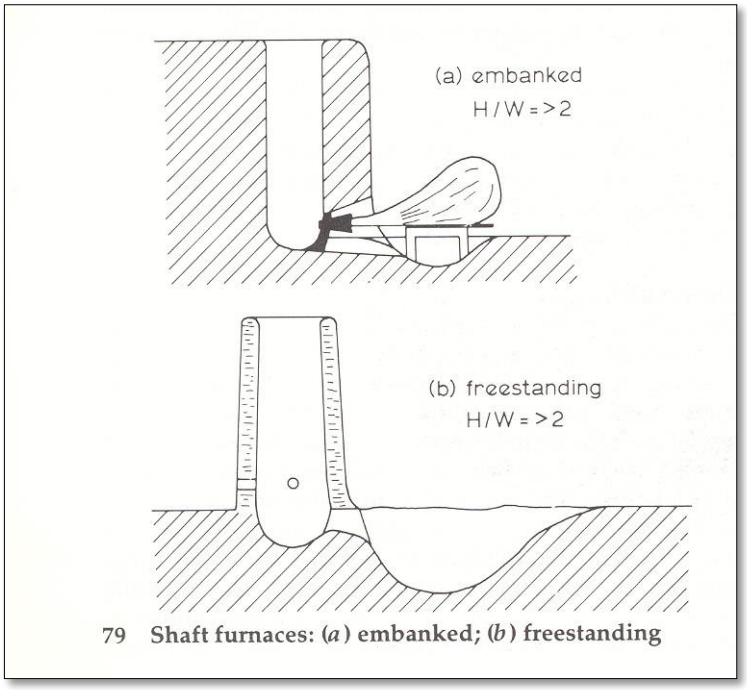

Figure 7, Tylecote's Embanked and Freestanding shaft furnaces

A variation of the freestanding shaft furnace is the slag pit furnace, where the shaft is built above a pit into which the slag descends to fill rather than filling the base of the furnace or being tapped. Interestingly Tylecote does not discuss the removal of slag from the furnace as a factor in the difference between furnace types, but rather uses the furnace structure being the defining factor.

Both of these categorisation of furnaces attempts to impose supposed methods where the knowledge is not fully known. The full height of a furnace will not survive archaeologically, some sites have the lower portion of the shaft preserved but even this is rare. Therefore, dividing the furnaces by the height vs width ratio suggested by Tylecote is not really possible in archaeological examples. Also, the shape of the shaft as suggested by Cleere is not a logical way of assessing the type of furnace as such a small amount of shaft will survive that it would not be possible to determine the difference between cylindrical or conical shapes.

Pleiner (2000) discusses the difference in the separation of the slag from the metal as the difference between furnaces. Firstly, furnaces where there is no provision for the removal of slag before the metal with the slag being contained within the furnace until the smelt is complete. Secondly, the slag being to allow the slag to descend to the lower portion of the furnace and remove the slag by raking if in a pasty or viscous state or to tap it in a liquid state if possible. The third method of separation was to use a pit located below the furnace shaft to collect the slag as it descends rather than removing from the front of the furnace. He also compared the method of how the metal would have been removed from the furnace, with the more open bowl furnace requiring the metal being removed from the top of the furnace while the metal is still hot. Where the slag was removed the iron could be either removed from an arch at the base of the furnace whilst the furnace was still hot or left to cool within the furnace. The first possibility seems to be the case when looking at archaeological examples, where there is little evidence for metal in the larger slag blocks.

How the furnace was operated is inextricably linked to how the smelting process was carried out and what products were possible. Despite a wide range of different furnace types which have been excavated and observed ethnographically each of these different furnace designs was successful at producing the desired product. It is also very difficult to ascribe a typology based on a single parameter such as the furnace shape, without considering other important parts of the process. Shaft furnaces, for example, may have very similar structures even if they differ in the removal of slag but how they would have been operated is likely to have been very different, as would the finished products. These differences would have been based on local conditions and traditions as well as practical purposes.

Each furnace, perhaps uniquely tied to its chronological and geographic place, was also embedded within a series of cultural parameters which would have impacted the 'how' and 'why' of the furnace construction and operation. To have a reliable and functional typology, it would ideal to have 'live furnaces' to fill the blanks from the archaeological record. However, the geographical and cultural variation between furnace types mean that typologies based on ethnographic examples can only inform us in general terms. The gap left may perhaps be partially filled by the judicious use of experimental reconstructions of iron smelting.

Experimental iron smelting events have fallen into two categories – trying to reconstruct what was discovered archaeologically and trying to recreate and record the metallurgical processes. These could be described respectively as reconstruction and experimental. It is this first category which is more relevant to the structure of a furnace. Based on archaeological remains a large number of furnaces have been reconstructed. Some aspects of the furnace do not survive archaeologically and they have to be estimated, the height of the furnace, position and number of tuyeres (if present).

It is the opinion of the author that strict furnace typologies are fundamentally flawed as they are based on what has been found previously and interpreted using ethnographical examples. A better approach is to have a more descriptive method discussing how the furnace was operated rather than deciding how the furnace was operated based on its form. Experimental furnaces are either based on archaeological remains (often missing the standing structure) or on the idea of what a furnace would have been. The variety of furnaces observed in ethnographic studies illustrates the spread of possible furnace designs which successfully produce iron. Aspects of the 'established' typologies have been discussed and dismissed as new discoveries are made and better understanding of the technology is achieved. Forcing furnaces into typologies has partially been addressed by

work such as Serning (1978) who addressed the issues with limited typologies. Serning created a double layer of typology with a tiered method of classification of the furnace design (I-V), structural material (a-c), slag separation (A-C) and air supply (1-3). However, there are still unsatisfactory 'forced' decisions in this classification, based on the size of the furnace.

A clear example of this is the bowl furnace, first postulated as the understanding of small furnaces without superstructure, dismissed as being incapable of containing the reducing gases required for the reduction of iron oxide by carbon monoxide, before experimental work showed the possibility of it working. Success in experiments does not guarantee this type of furnace existed but it shows that it is possible.

2.1.5 Furnace Furniture

Furnace furniture is another aspect of the iron smelting process which can be hard to study from the archaeological record. Furnaces are fairly simple systems with the only additional parts being bellows and tuyeres for the introduction of the airblast. No archaeological examples of bellows have been found from this period, as they would have been made of organic materials such as leather and wood, and the waterlogged conditions that would best preserve these are not conducive to smelting. Therefore, we have to approach other disciplines to get the information we need to begin to answer these questions. Where present, literary and iconographic sources can give us important clues otherwise also using ethnographic sources are the best alternative available. For the later prehistoric period, we have no iconographic or relevant literary sources therefore ethnographic sources are more important. For the Roman period, we have iconographic evidence illustrating what equipment may have been used.

The use of bellows has been considered crucial for the success of early iron production however it is possible to produce iron from natural draft furnaces. These have been observed ethnographically (Chirikure and Bandama 2014, 296-297) and archaeologically (Chirikure *et al.* 2009, 198-199; Juleff 2009, 560). These examples are considered to be the end of a long established development of furnace design. There are two forms of these; natural draft which employs the chimney effect to draw air through the furnace and forced natural draft which uses a consistent wind instead of bellows (Tabor *et al.* 2005, 754). They also utilise unique and predictable weather and winds to ensure a successful smelt. A consistent wind speed would be crucial to the success of a smelt, fluctuations in wind may have led to fluctuations in reduction conditions and temperatures (Tabor *et al.* 2005, 763). The unpredictable British weather would mean that this type of furnace would therefore be less predictably successful than a forced draught furnace. This would suggest that a predictable and controllable airblast from a set of bellows would have been required. There are a number of designs of bellows which have been used across the world over the recorded history of metallurgy. Four main types have been described: bag, pot (or bowl), hinge, and box (Chirikure *et al.* 2009, 200). *Bag bellows* consist of a sealed bag with a controllable opening to allow air into the bag which can then be driven through the nozzle. *Pot bellows* have a skin of hide or leather over a pot which is systematically lifted and depressed to fill and empty the bellows (Chirikure *et al.* 2009, 200). *Hinge bellows* are formed of two flat plates hinged at the tuyere end and connected by a flexible membrane at the other (Pleiner 2000, 214). Finally, *box bellows* operate as a pair of opposing pistons one filling while one is emptying (Huang *et al.* 2015, 49; Juleff 2009, 573).

Bag bellows have been observed predominantly through ethnographic studies in Africa. These examples were made from animal skins. These were sewed up to form a sealed bag with two openings, one fixed opening for the expulsion of air through the tuyere and one

controllable opening which could be opened to fill the bag (Chirikure *et al.* 2009, 201). This appears to be a fairly basic form of bellows which requires only a flexible airtight membrane to create a forced draft for a furnace. As well as these ethnographic examples, Theophilus Presbyster described how to make bag bellows from the skin of a ram (Theophilus and Hawthorne (trans.) 1979). Pot (or drum) bellows have also been observed from ethnographic studies in Africa (Miller, van der Merwe 1994; Chirikure *et al.* 2009, 200). They are formed of a solid chamber with a flexible membrane at one end which is worked to create an air draft. Observed examples have been made of ceramic vessels modified to form the chamber and specially made wooden chambers.

There is no confirmed archaeological evidence of hinge bellows, but there are examples of contemporary iconography from the Roman period in Europe, although these images are only of blacksmithing equipment (Pleiner 2000, 214; Manning 1976, 6).

These three types of bellows all have one key drawback, the full cycle of operation consists of a downstroke and upstroke – expulsion and intake of air cyclically. Therefore, there is a relatively long period where there is no air being forced into the furnace. These therefore are best operated as at least a pair to ensure a continuous stream of air into the furnace. If operated singly the conditions within the furnace would be more difficult to maintain at a desired level.

One aspect of furnace furniture which is found on archaeological sites and can give us useful information are tuyeres. They are the vital connection between the bellows and the furnace. Bellows have to be airtight and flexible enough to force air into the furnace, however the materials which are best suited to this are also flammable, leather and wood being the most commonly used. Having these too close to a furnace at full temperature will result in a catastrophic failure of the bellows. Therefore, it was necessary to have a fire

proof connector between the bellows and the furnace (Pleiner 2000, 196). Tuyeres have been recovered from a number of archaeological sites, sometimes in surprisingly high quantities. The most common form is a conical form tapering from the bellows end to the end inserted into the furnace although square tapering versions have been found from Roman sites. Fragments of tuyeres are the most likely piece of furnace furniture to survive as they are made from baked or fired clay which is further fired by the proximity to the furnace leading to the tip often becoming vitrified by the heat of the furnace. The conical form of many tuyeres gives an increased airflow from the bellows into the furnace. This would also have the benefit of having a smaller break in the wall of the furnace (Pleiner 2000, 208).

The location and number of tuyeres control the location(s) of the different zones of chemical reactions and temperatures within the furnace. There are ethnographic, historic and well preserved archaeological examples of successful furnaces being operated with a number of tuyeres operating in conjunction to fire larger furnaces and form larger blooms than would be possible using a single set of bellows. The most famous of these are the Tamahagene furnaces of Japan, famous for the production of steel for the production of Samurai swords. Cleere (1985, 161-163) discusses the types of different tuyeres and their association with furnace types in the Roman Weald. There is a correlation between multiple single tuyeres and Cleere's B.1.ii and double tuyeres and B.1.i furnaces. The double tuyere allowed for a greater airblast into the furnace by combining two bellows into a single tuyere. All have a cylindrical rather than conical tube so they were not designed to concentrate the airblast. When compared to experimentally made examples the tuyeres appear to have been 'leather hard' rather than baked or fired (Cleere 1981, 163). There are few examples of tuyeres from Iron Age iron smelting sites, this can be attributed partially to the poor survival of poorly fired clay in the archaeological record. It may also be a

representation that the iron age smelting process operating in a slightly different fashion, using a ‘blowing hole’ rather than a tuyere (Crew 1991; 2013). If a tuyere did not extend into the furnace it may not have become vitrified or slagged to the extent where it could be preserved in the archaeological record.

2.2 SLAG

2.2.1 What is it?

Slag is defined in broad terms by both non-specialist and specialist sources:

'*A vitreous substance, composed of earthy or refuse matter, which is separated from metals in the process of smelting…*' – Oxford English Dictionary (2017)

'*Slag is the glass like by-product left over after a desired metal has been separated from its raw ore. Slag is usually a mixture of metal oxides and silicon dioxide…*' – Wikipedia (2017)

'*In very general terms, slags are waste, ie. discarded or left behind evidences of human activity, difficult to classify and to date, but remarkably resistant to weathering*' – Bachmann (1982)

These descriptions cover many of the aspects of this material, but are potentially misleading. The problem is that they only cover one potential source of this complex material type. Slag is a sweeping term which needs to be further defined to give the individual materials and methods involved in its production. There have been a number of attempts to define slag recovered from archaeological sites, but the majority of these have been limited by process, site or geographical region. Therefore, these have not addressed the overall question of defining the different types of slag. Slag can firstly be subdivided into deliberate and accidental, with the deliberate material further subdivided into production and processing, then yet further defined by material. There are two types of accidental slag or slagged material – fuel ash slag and accidentally vitrified building materials (Dungworth 2015, 60-61). Fuel ash slag is a vitreous slag formed by the reaction of the alkali rich ash at high temperature. This is not diagnostic of any one pyrotechnological process as it simply requires a high temperature and a combination of silica and alkali elements (Henderson *et al.* 1987, 363; Biek and Bayley 1979, 6). Vitrified or slagged building materials are formed by a structure being subjected to very high

temperatures, a type which is represented on many production sites by furnace lining. There are also building materials which are not related to high temperature processes which have becoming ‘slagged’. Timber framed buildings with clay walls, which have burnt down, leave slagged fragments of daub (Dungworth 2015, 61). These are all technically slag and can easily be mistaken for deliberate slag by untrained observers.

There are many forms of deliberately produced slags and they are linked to their process by their basic descriptive names. For example, iron smelting slag which was produced during the smelting of iron. Deliberately produced slag has a defined role within the process which is crucial to the success of the overall process. Deliberately produced slags could be further categorised into production and refining slags. The role of a production slag can be roughly defined as being the separation of desirable and undesirable portions of the raw materials so that the desired product can be produced; however, the details of how this functions are different for each different material.

There are three types of iron slag commonly found on archaeological sites: *smelting*, *smithing* and *undiagnostic* slag. They are intrinsically compositionally similar but the differences between the smelting and smithing processes create different macromorphological, micromorphological and chemical compositions (McDonnell 1995, 6). Undiagnostic slag is not clearly produced by either the smelting or the smithing process. This material is usually too small or fragmentary to be definitely linked to either smelting or smithing (Dungworth 2015, 24). When found on a definite smelting site it may be representative of the initial processing of the metal from the furnace or bloom smithing. Smithing slag is produced during the process of working iron through heating and hammering to change its form. The slag is formed of slag squeezed from the raw iron, plus hammerscale and small fragments lost from the iron; this reacts with the fuel and its resulting ash as well as with the lining of the hearth to form slag. The smithing process has

fewer impurities that need to be removed when compared to the smelting process. Therefore, the amount of slag created during a single smithing event is less than during a single smelting event of a comparable size (McDonnell 1995, 6).

The slag from the bloomery iron smelting is a complex mixture of mineralogical phases; it is in many ways an artificial rock. Iron slag is generally described as being fayalitic after the main mineral phase present in the slag, fayalite (Fe_2SiO_4 or $2FeO.SiO_2$) (Bachmann 1982, 14). This mineral is a product of the main constituents of the iron ore; iron oxide and silica. The silica content of the slag usually ranges from 15% to 40% (with greater than 34% considered high) (Pleiner 2000, 252). As well as the fayalite crystals, which are often dominant, there are two further phases which are present in almost all direct smelting slags. Free iron oxide in one of its oxide forms most commonly wüstite (FeO) but magnetite (Fe_2O_3) can also be observed (Bachmann 1982, 15). The wüstite content of slag can reach as high as 70% (above 50% is considered high) and magnetite in the form of unreduced ore or reoxidised wüstite can reach up to 15% (Pleiner 2000, 252). The final major phase is the glassy phase, this consists of the remaining elements which have not formed the crystalline phases. These other elements include the alkali elements phosphorous, calcium, potassium and titanium. As well as these phases metallic iron is a common feature of smelting slag (Bachmann 1982, 17). It can be found in a number of different forms, sometimes as fibres which have begun to be welded together as part of the bloom formation. Smaller fragments of metallic iron can be observed in the slag mass having been transported down below the bulk of the iron located near the air inlets (Pleiner 2000, 253). Tholander (1987) suggested that these metallic particles fitted within a typology which relates to a specific point in the smelting process. Beginning with the formation of a metallic shell, the fragments of the shell and compacted pieces of iron start formation of a bloom.

The combination of these phases mean that slag is a complex mixture of silicate and oxide phases in a glassy or crystalline state. As well as these very common phases there are a number of mineral phases which are also found in smelting slag.

Slag is a crucial factor in the reduction of metals from their ores, especially in the direct iron smelting process. The reasons for this will be explored and explained further in the rest of this chapter. Iron smelting slag is a combination of the gangue elements of the ore, elements of the fuel ash and furnace lining in varying amounts (Charlton 2007, 107). The gangue elements of the ore need to be separated from the metallic iron, this is the main role of the slag. This most obvious function of slag, to remove what is not wanted in the iron can be considered in two related routes, physical and chemical separation (Charlton 2007, 92). The nature of the direct smelting process and its production of metal in the solid state requires the slag to be liquid for the physical separation to happen. If this does not occur, then there are a number of problems which will result in an unsatisfactory smelt. If there is no separation of the slag and metal then a defined bloom will not be produced. Even if there is separation, but if it is incomplete, then the iron will be difficult to work and have reduced properties. A large amount of slag left incorporated into the metal would have to be removed by repeated smithing, the bloom would have to be heated and hammered to squeeze the slag from the bloom. If this is not achieved, the slag will cause weaknesses in the metal increasing the likelihood of a fracture during the working of the iron (Sauder and Williams 2002, 129). This repeated smithing would require large volumes of charcoal for fuel and would result in the loss of metallic iron to iron oxide in the form of hammerscale (Dungworth and Wilkes 2007).

There *are* beneficial roles of the slag; a liquid slag allows the transport and collection of the iron particles into a bloom. Additionally, the mass of molten slag acts a heat reservoir, preserving the energy needed for the endothermic reactions creating carbon monoxide and

reducing the iron oxide to metal. Finally, slag protects the bloom and iron particles from oxidation in the combustion zone. Therefore, slag is an indispensable part of the bloomery process (Charlton 2007, 94).

A crucial factor in the physical properties of the slag is the liquidity. This is a direct consequence of melting temperature and the viscosity of the slag. These are both directly affected by the composition of the slag (Kresten 1986; Freestone, 1988). The composition of the slag is determined by the composition of the ore, technical ceramics and fuel ash. Each of these will contribute certain elements to the composition of the slag and therefore the resulting slag is directly linked to the composition of the raw materials. Some of the elements can be contributed from multiple sources (table 2). The viscosity and melting temperature of the slag are related directly to this composition (Bachmann 1980, fig 6; Rehren *et al.* 2007, 212). With liquidity being a function of these two factors the composition of the slag is linked to this.

	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Ore	X	X	X	X		X	X	X	X
Clay		X	X		X		X		
Fuel Ash	X			X	X	X			

Table 2 (Adapted from Charlton et al. 2010, 355)

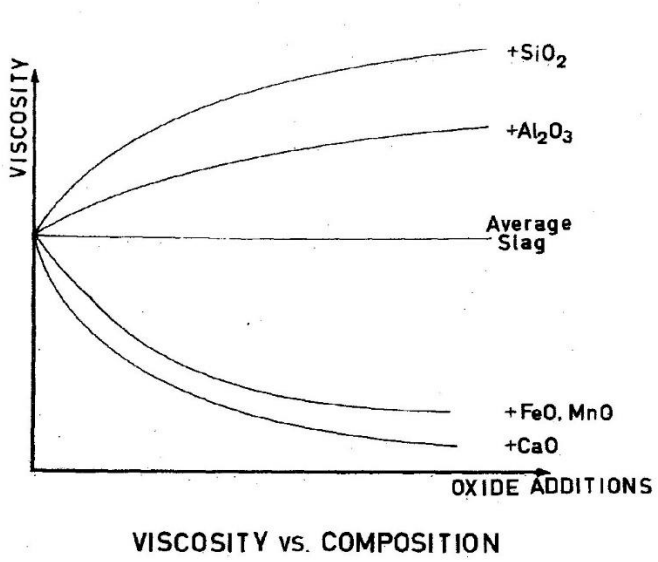

Figure 8, Slag Viscosity vs Composition (Bachmann 1980, 131)

It is not simply a case of making the slag as liquid as possible to separate it from the metal, the slag also plays a crucial role in protecting the iron during the smelting process (Sauder and Williams 2002, 129). If metallic iron were to be left exposed in the conditions within the furnace then it would be exposed to redox conditions which would alter the metallic iron. If the iron was exposed to reducing conditions then the carbon content would increase. This would have the effect of lowering its melting temperature making liquid iron possible at 1273°C (Tholander and Blomgren 1985, 417-418). While cast iron is a commodity which is commonly used in the modern period, and was exploited at a very early date in Asia, and China in particular, it was not deliberately produced in Britain until the 15th century AD (Bayley *et al.* 2001, 4). Nonetheless, cast iron is likely to have been produced accidentally in highly carburising furnaces (McDonnell 2013, 66). Whether the lack of cast iron stemmed from a technological inability to produce this material or an unwillingness is a matter for discussion elsewhere, but in any case, cast iron would not have been suitable for the objects which were commonly produced from iron during the period of this study. If the metal was exposed in oxidising conditions then it would be transformed back to its oxide forms rather than its metallic form. This would reduce the yield of iron from the

smelt, potentially losing all the iron formed earlier in the process. The close control of the liquidity of the slag during the smelt is therefore crucial in the type and quantity of iron produced.

Chemical separation is not as readily understood in the antique smelting methods, many of the conclusions of which have been drawn are based on more modern metallurgical methods applied retrospectively onto archaeological material (Clough 1987). There have been problems with this method of combining sources of information as the level of control within modern smelting is focussed on different outcomes than ancient smelting. There are a series of elements which will alloy with iron; some of these, such as carbon, have accepted beneficial properties (Samuels 1980, 41). However, others, such as sulphur (Clough 1987, 68) have negative properties, whilst a third group, such as phosphorous, have both negative and positive properties (Godfrey 2007, 20). It is certainly the case that in modern metallurgical practices, careful control of the chemical composition of the slag is used to control the impurities of the iron or steel being produced. Proving that the chemical composition of the slag was controlled, or even controllable, to the degree required to affect the outcome of an ancient smelting event is very difficult. The observable properties of the slag would be the only way of examining the composition of the slag without modern analytical equipment. The viscosity of the slag is the best suited for this, as it is observable within the furnace and directly related to the composition. Given that certain slag compositions have the potential, based on modern metallurgical knowledge, to affect the quality of the iron, this is likely where the idea develops that certain regions are good or bad for the production of different types of iron. The unique combinations of ore, fuel, and furnace material from each smelting site will result in differences in the slag and metal. There is some accepted partitioning of elements between the slag and the metal.

Some will only pass into the slag, some only into the metal and some between the two (Charlton *et al.* 2010, 355).

The form of slag reflects what process or part of a process it was involved in at the point it solidified. Diagnostic slag from the smelting process is divided into two groups – that which solidified within the furnace and that which solidified outside the furnace. Slag which solidified within the furnace takes the form of what it was interacting with when it solidified: furnace bottoms, slag blocks, and furnace slag. *Furnace bottoms* are formed at the base of the furnace by the earliest forming slag in the smelt, it descends through the charge of the furnace to form a solid mass below the hottest portion of the furnace. These can be formed in both slag tapping and non-tapping furnaces, in a slag tapping furnace the upper surface of this mass reflects the height at which the slag was tapped from the furnace, they are less common and not as thick from slag tapping furnaces as the slag was tapped out (Crew 1995, 2). *Slag blocks* are formed in slag pit furnaces, the pit below the furnace shaft was used to collect the slag allowing for a longer smelt by having a reservoir for the slag. These have been confused with furnace bottoms but the difference is that these are deliberate removals of the slag from furnace into a pit below. The pit would have to be blocked off with combustible material to support the furnace charge until the slag began to form and drain into the pit (McDonnell 1986, 130). This type of slag will show the size and shape of the slag pit into which it drained and also what material was used to support the charge at the start of the smelt. *Furnace slag* is formed within the furnace but not at the base of the shaft or bowl, or drained into a pit below. This material can form in contact with the furnace walls and show the furnace shape, it can also form in contact with any unburnt fuel or material used at the base of the furnace to support the charge. Furnace slag is not diagnostic of the furnace operating method itself, but its percentage of the entire assemblage can be.

Slag which solidified outside the furnace forms two main types, *tapped* and *raked* slag. *Tapped slag* is slag which was deliberately drained from the furnace in a liquid state to stop the accumulation of slag interrupting the airflow into the furnace. To be able to flow from the furnace, the slag has to be liquid enough to flow under the force of gravity alone (McDonnell 1986, 88). *Raked slag* would not have been liquid enough to flow from the furnace and had to be manually dragged out from the front of the furnace. This material can also be the result of removing the bloom from the front of a non-tapping shaft furnace (McDonnell 1986, 114).

A further type of slag which is not fully understood is *slag tubes* or *rods*. These have been formed by slag solidifying in a tubular void, and there has been much discussion about the nature of the voids in which these were formed. Schrüfer-Kolb (2004, 9) suggested that these were the result of slag flowing into a tuyere once the airblast had been halted. This would seem unlikely when considering larger tubes (McDonnell and Swiss 2004) or stacks of tubes (Bray 2016, 12).

Undiagnostic slag is also commonly found on smelting sites, it falls into two categories, undiagnostic because of damage and because of form. Fragmentary slag can be too small or retain none of the surface features which allow it to be definitively connected to either smelting or smithing. Slag that is undiagnostic because of its form is generally small in size and often small runs of slag which solidified within a bed of charcoal. As this could occur in any part of a furnace, bloom hearth or smith's hearth, it can be difficult to connect to any single process without further information. The composition of the rest of the assemblage or the volume of material could inform what process created this slag.

Slag is formed from the interaction between the gangue minerals, fuel ashes, and a portion of the technical ceramics (Charlton *et al*. 2010, 355). The slag's role is to separate the

gangue from the metal, then to separate the slag from the metal, this separation is dependent on the viscosity and melting temperature of the slag. These properties allow it to both interact with and flow from the iron. In the tuyere zone, slag coated metal is relatively unchanged as the residence time is too short; if the slag is too free flowing, then the high temperature would cause the slag to liquidate and drop away from the metal. This leaves it exposed to oxidation and means that if the metal is carburised then a degree of decarburisation can occur. If it is not carburised then the oxidation of some of the iron can lead to it being reincorporated into the slag. The slag's role is to protect the metal in this zone, but this is dependent on its viscosity (Sauder and Williams 2002, 129; Sauder 'Update on the "Practical Treatise", 2).

There has been considerable focus on the slag recovered from iron working sites, in part due to the predominance of slag on sites, given that often, few other elements of the smelt remain. Equally, with a growing understanding of the process, the significance of slag to the smelting process is more obvious (Charlton 2007, 94). Many previous studies had the emphasis on the role of the slag in the formation of the bloom, declaring that a self-fluxing ore was necessary. This is due to the assumption that "to get low carbon metal and free running slags demanded by the bloomery process, we must have large iron losses in the slags and reduced yields" (Percy, 1864, 352). While this is partially true, the fact of the matter is that self-fluxing ores are simply easier to utilise in the bloomery furnace. Very rich ores such as high grade hematite have apparently as being used in a smelting process which results in a bloom of iron with almost no slag, but even the author considers it to be dubious (Pleiner, 2000, 251).

Slag has a threefold function, it is a vessel for the gangue minerals, an absorber of impurities in the metal and a protector of the bloom. The main function of the slag is by the processes described above to form a liquid mixture of the gangue elements of the ore

combined with the ash from the fuel and contributions from the furnace lining. By incorporating these into the slag they can separate and remain separate from the metal. The absorption of the impurities is a secondary role but important in the removal of phosphides and sulphides. The protection of the bloom can prevent excessive oxidation in the combustion zone of the furnace. It can also play a role in the decarburisation of the bloom, to achieve such functions slags must have certain physical properties (melting point, viscosity) and chemical properties (basicity, oxidation potential) these are controlled by variations of composition and structure. These all have given rise to the maxim '*good slag, good steel*' which, although inspired by modern processes, also applies to antique methods.

2.2.2 Slag analysis

The analysis of iron smelting slag was not conducted by archaeologists but by metallurgists, which led to inevitable comparisons with modern processes. There are different levels of analysis which could be carried out ranging from basic weight and frequency through macro and micro analysis to chemical analysis.

2.2.2.1 Previous work (general/global)

Slag analysis has been carried out almost everywhere that ancient iron smelting processes have been identified as it is the key method of understanding iron production. The amount of slag analysis carried out matches the amount of archaeological work in general which is carried out but also the amount of importance placed on iron. The most widespread study of slag has been from Europe, the region which has pioneered most of the analysis of this material (Pleiner 2000, 252).

The examination of slag has been along three main pathways, macromorphological, microstructural and compositional. These three pathways have not been equally studied with the basic macromorphological analysis being commonly used to determine what slag was being analysed for further compositional work. Detailed macromorphological work

has been limited and has not always used to further understand the smelting process (Mikkelson, 2003). Microstructural analysis has not been consistently employed as an analytical method, it is either employed in great detail or barely used or even ignored in preference for the analysis of the chemical composition. Chemical compositional analysis has become the most widely reported method of analysing slag. This is partially due to the direction the studies have attempted to take, trying to connect metallic iron to the smelting process (Godfrey, 2007), provenancing ores (Paynter 2006; Brauns *et al.* 2012; Mameli *et al.* 2014; Charlton 2015), quantifying the efficiency of the smelting process (Joosten *et al.* 1998) and understanding the raw materials used (Killick and Miller 2014). While some of these works also include macro and micro morphological analysis, the three methods are rarely combined to give a complete picture of the slag, its properties and its role in the smelting process.

The macromorphological study of slag was focussed on the identification of slag as a marker of metalworking, rather than a tool to understand metalworking. The general form of slag has been used to determine the type of furnace in operation with a split between slag retained within and slag tapped from the furnace. The work of McDonnell (1986) is among the first to attempt to define the differences between smelting and smithing slag. The definition of the different types of slag has been completed by several academics (Fells 1983; McDonnell 1986; Young 2014a; 2015) and these studies have either built upon existing work, adding new types when different forms were discovered or have instead rebuilt the typology to suit their study area. As the types of slag and the diagnostic information held within them can be very specific to the chronological period and geographical region, It is only with work such as Mikkelsen (2003) that the intricate details of slag macromorphology began to be explored in more detail. Mikkelsen used the impressions left in the surface of the slag from slag pit furnaces to look at agricultural

practices, with the impressions of straw in the base of the slag blocks revealing how the grain had been harvested.

The microstructural analysis of slag was first carried out during the 19th century on contemporary slag, this identified that there were occasionally minerals present which could be related to known geological minerals. The identification of an olivine group mineral in slag occurred in the 1870's. By the 1920's the mineralogy of archaeological slag began to be examined (Cunnington 1923, 53). It is not until the work of Morton and Wingrove (1969a; 1969b; 1970) that a study of slag from multiple sites comparing mineralogy to chemistry was completed.

Pleiner (2000, 256) briefly summarised the history of the chemical analysis of slag with the first analyses being small in number and originating from Germany. During the post-war period, the systematic analysis of waste and raw materials increased as more sites were excavated (Pleiner 2000, 256). Despite analytical centres being established across Europe, there still remains large areas where there the data available for comparison are patchy (Pleiner 2000, 256).

Pleiner (2000, 252) used the analytical results of nearly 70 years of work across Europe to provide the ranges of slag composition which have been observed. The number of countries in which this work was produced, and the range of languages in which they were published, can make them difficult to access.

From the study of modern blast furnace slags it was suggested that their properties could be determined by the mineral phases they contained and not merely the oxides they contain. This was used as a concept by Morton and Wingrove (1969a; 1970; 1972) to use phase diagrams to study the melting temperatures of bloomery slags. They proposed therefore that using the anorthite, FeO, SiO_2 system that the liquidus temperature of the slag can be

estimated. These were the first in depth studies of ancient slag which married up chemical composition to mineralogy of the slag. They set out the principles of how analysis should be carried out to be able to estimate the melting temperatures of smelting slags. These principles have been used as the basis for many of the analyses that followed. They also claimed that the amount of wüstite present in the slag was a reflection of the slag-metal reactions during the smelt and that this was a reflection of the skills of the smelter (Morton and Wingrove 1970).

The first, and to date of this writing, only attempt to make a coherent single volume on ancient slags was Bachmann's work from 1982. This work explicitly states it is not a monograph on slags in terms of extractive metallurgy or mineralogy (Bachmann, 1982, v). It is set out as an introduction to slag for anyone in the field of archaeology, from site worker to the scientist brought in to contribute to the post-ex, but has become the only standard text for mineralogical analysis of slag. This volume describes the process of identification and analysis of slag from site to laboratory. Bachmann's work up to this point had been primarily based on the smelting of copper and the role of slag in this process (Bachmann 1980). There are many similarities between the slag produced by copper and iron smelting, since many copper ores have sufficient iron content to result in similarities in the composition and mineralogy of the slag (Bachmann 1982, 10). The aim of Bachmann's work was not to produce the standard reference volume in this field, but rather to allow for the further discussion and research into a complex and underdeveloped area. However, as a suitable follow up volume to fill such a role never emerged, the book has come to be treated as the reference monograph for archaeological slag. It has limited scope into the processes that affect the slag chemistry and mineralogy or into what effect changing chemical composition has on the properties of the slag.

Some of the most accessible accounts of iron working and slag's role within it have been as part of wider archaeometallurgical works. Tylecote (1987; 1990) and Craddock (1995) have covered the wider iron smelting process, including the distribution of sites, furnaces and the metal product. Pleiner (2000) focussed on the smelting of iron through the bloomery process, with a concentration on Europe, in which much of the existing research into slag and its role in the iron smelting process is brought together. The author included a detailed survey of the composition of smelting slags from across Europe and compared hundreds of analyses. The chemistry and mineralogy of the slags is discussed in detail but Pleiner did not include images of the different minerals commonly found. The discussion and illustration of the micromorphology of the slag is clearly set out in two main types; the slag retained within and removed from the furnace.

In terms of the global study of slag, work carried out in Asia and Africa have developed along slightly different lines to European studies. African smelting studies have been heavily influenced by the recent history of this continent, a result of colonial powers and ethnographic studies. European explorers of the 19th century recorded the 'primitive' iron production processes being carried out across Africa. While these ethnographic records of the smelting process have been identified as ameliorating the missing 'human factor' in the archaeological record, they have not been utilised until recently. Rehren *et al.* (2007) was the first to incorporate this human factor alongside the slag composition in the consideration of how that would affect the smelting process. The tendency of the examination of iron smelting in Africa has been to try and prove, or disprove, the idea of independent invention, primarily through the application of radiocarbon dating, to find earlier and earlier sites. Progress in scientific studies of smelting has been slow due to the scarcity of trained archaeometallurgists and the shortage of funding for chemical and

metallurgical analysis (Killick 2015b). The major benefit to the analysis of slag that has come out of African archaeology has been to look at more than just the practical metallurgical reasoning behind chemical compositions and to look at the human side of the smelt (Rehren *et al.* 2007).

The study of iron smelting in Asia has often been more linked to the artefact (Park *et al.* 2010) or to the production of liquid iron (Feuerbach 2006; Lam 2014). Therefore, less focus has been given to the bloomery smelting process and slag. There also appears to be a fundamental difference between continental and maritime Asian iron production (Juleff 2009, 568). The maritime trend is for linear arrangements of tuyeres to form straight sided batteries of reduction zones. This arrangement spreads from Sri Lanka, around South East Asia, to Japan and culminating in the famous Tatara furnaces (Juleff 2009, 573). Korea appears to have been the buffer zone between a series of iron smelting technologies. Cast iron artefacts of a type only found in Korea indicate a connection to China, while bloomery smelting sites and artefacts suggest a possible connection to maritime Russia (Park and Rehren 2011, 1190).

2.2.2.2 Previous work (period/region specific)

Estimations on the size and scale of iron smelting activities were first carried out by the antiquarians of the 19th century who worked on the sites of the Roman Weald. The slag heap at Beauport Park, which had been mined for hardcore to construct roads in the local area, was recorded by the local priest. While a quantification of the process was not attempted, the scale of the site was understood to be significant. Some of the key works on smelting slag have been focussed on smelting slag from Roman sites in Britain (Morton and Wingrove 1968; 1970). The significance of Morton and Wingrove's study on global slag studies has been emphasised in Anglophone archaeometallurgical literature; while there were earlier continental studies, their work was crucial in the study of smelting slag

from British sites. Subsequently, Fells (1983) produced a comprehensive study of slag from excavated Iron Age to Medieval bloomery sites from Britain. The mineralogy of the slag was confirmed by electron microprobe analysis which revealed that hercynite and leucite were common phases along with fayalite, wüstite and glass.

More recent work has been through two main avenues, either academic research (Schrüfer-Kolb 2004) or developer led (Young 2003; 2004a; Girbal in Allen *et al.* 2013; Crabb in Lewis *et al.* 2013; Allen in Pine *et al.* 2010), there are also a number of unpublished doctoral theses looking at technical details or comparing compositions from different regions (Fells 1983; McDonnell 1986; Clough 1987; Stetkiewicz *in prep.).* The key difference between these is the motivation - a research project will set out with a particular period, region or hypothesis to study while a developer led project will be driven by the opportunity presented by the location designated. Most of the in-depth research and especially over a wider geographical or chronological scale is carried out as a research project. A third route, which sits somewhere between the two above, is the work being carried out by Historic England (formerly English Heritage). This body conducts academic research style work but often on material from developer led sites or with the aim of supporting developer-led archaeological projects (Bayley 2001; Dungworth 2015). The Historic England laboratories have produced in-depth scientific analyses of iron smelting remains for over 30 years, as well as reports on slag recovered from archaeological excavations (Starley 1997; 1997; 1998; McDonnell 1988; Paynter 2002) and technical reports on experimental reconstruction (Dungworth and Wilkes 2007; Paynter *et al.* 2012). Paynter (2006) is one of the key papers on Iron Age and Romano British iron smelting, as it focusses on the potential to connect slag to ores, and potentially, to metallic iron. To do this, Paynter undertook new analyses of slag but also used existing analyses from key sites to understand the interaction between the ore and slag composition at Iron Age and

Romano-British smelting sites. This is also notable as one of the first attempts at a large scale geographical study of slag across Britain in these periods.

The three main areas of iron smelting in Britain[2] have dominated the study into iron smelting but this does not necessarily transfer to the study of slag. For example, the Weald has been heavily studied by the Wealden Iron Research Group (WIRG); however, as an amateur archaeological group, it does not have access to the funding to contract for analysis or the equipment to carry it out themselves. The WIRG recognise this as an issue and that they are in the privileged position of having a large corpus of data; they are willing donors of slag for analysis where appropriate (Hodgkinson pers comm). A small number of sites from the region were analysed as part of Paynter's wider project into Iron Age and Roman iron smelting (Paynter 2006; 2007).

Outside of the Weald, there is not the same apparent level of amateur archaeological organisation and involvement. In the Forest of Dean and the Jurassic Ridge, despite a smaller extent to the work conducted, there are still key syntheses which have explored the whole of each region. Amongst these is the study of the Iron Age to Roman transition in the Northamptonshire Jurassic Ridge by Schrüfer-Kolb (2004). While there is analysis of the slag from the sites in this monograph, slag was not the main focus of the publication. Fells (1983) analysed slag from this region as a part of her doctoral research into iron smelting in Britain.

Most of the slag analysis work carried out in the Forest of Dean have been incorporated into individual excavation reports (Fulford and Allen 1992; Young 1999; 2004b; Young and Kearns 2010; Pine *et al*. 2010). Allen has been the main contributor to the geochemical analysis of slag from this region this has shown that the ore being exploited

[2] The Weald, Forest of Dean, and the Jurassic Ridge

in this region is the limonite ore from the carboniferous limestone underlying this area (Allen 1988; Fulford and Allen 1992; Pine *et al* 2010). This ore type leads to a slag with elevated levels of lime and magnesia and low levels of phosphorus (Paynter 2006, 286).

Outside of these regions which have come to dominate thoughts on iron smelting thoughts the analysis of slag was rarely carried out. More analysis of slag has been carried out with increased commercial work and widespread application of slag analysis (Lewis *et al* 2013; Ford *et al* 2013; Dungworth 2007; Girbal 2010; Young 1997; 2003; 2004a; 2005; 2007; 2008; 2012a; 2012b; 2013; 2014a; 2014b; 2015). This work has identified a number of regional ore sources but showed widespread trends in the smelting process across southern Britain.

The chemical analyses from existing studies have been complied to give a comparative database for the new analyses in this study (Paynter 2006; Girbal 2010; Young 1997; 1999; 2008; 2014a; 2014b). The more qualitative nature of macromorphological and mineralogical analysis is more difficult to compare between studies as it requires the conclusions to be confirmed by reanalysis, especially with no standardised reference material.

2.3 IRON PRODUCTION IN LATE PREHISTORIC AND EARLY ROMAN BRITAIN

2.3.1 Prehistoric iron production

The history of Iron Age studies

The Iron Age in Britain can be seen as dating from c.800 BC to AD 43, forming the transition from the prehistoric bronze and stone ages to the historic Roman and later periods (Johnson 1997, 308-9). The concept of the Iron Age was first devised by Thomsen as part of his three age system in 1836 but it was not until the excavations at Halstatt and La Tene from the 1840's to 1860's that chronological divisions could be made (Cunliffe 2005, 3). The coherent study of this period did not truly begin until the "Iron Age Archaeology" of the 1920's and 1930's (Hill 1995a, 51) and in particular the publication of several new excavations on hillforts and settlement sites across the country and Fox's work on La Tene Fibulae and a series of papers by Hawkes on the wider Iron Age (Cunliffe 2005, 3). Hawkes' work set out the philosophy that the Iron Age was a sequence of large scale migrations from continental Europe bringing the new material cultures observed on excavations (Cunliffe 2005, 4). Until this point the studies had been dominated by classical sources and the ideal of the Celtic peoples occupying Britain before the arrival of the Romans. A number of key excavations in Wessex led to the type sites and research frameworks which came to be used across the country. A three phase ceramic (Iron Age A,B,C) typology chronology was developed from sites in the south and south east with each phase being attributed to a different incoming culture (Hill 1995a, 51-52; Cunliffe 2005, 10). The following 20-30 years led to an increase in the number of excavations and the establishment of chronologies and frameworks to describe and understand this period (Hill 1995a, 51). The ceramic typologies were developed during this period to take into account temporal and spatial variation (Cunliffe 2005, 11-15; Hill 1995a, 52). The invasion

hypothesis which held up much of this work became entirely dismissed in the 1960's with the death knell being brought by Grahame Clarke (1966). This left Iron Age studies without a usable framework as the historical models collapsed, the void was filled with fresh ideas from the realm of 'new archaeology' (Cunliffe 2005, 20). Over the following twenty to thirty years increasing evidence and new ideas saw a dramatic change in Iron Age archaeology. However there still remained a geographical imbalance towards the south and east even with a dramatic increase in the number of sites outside this area. Through the 1990's and into the 2000's Iron Age archaeology developed with the introduction of new archaeological theories and the introduction of more scientific analysis being carried out on excavations (Hill 1995a, 53).

Despite some discussion over the exact positioning and number of divisions in the Iron Age it can be broadly split into an early, middle and late period chronologically (Hill 1995a, 47; Cunliffe 2005, 32) and into a south and east versus north and west regions geographically (Cunliffe 2005, 27- 28). More detailed studies of sub regions within these confirm that landscapes, resources, contact and exchange networks influenced each differently and that these studies reveal a series of complex pictures of diversity and inertia to external change as well as internal drivers for change (Davies, 1996; Hutcheson 2007; Moore 2006; Sharples 1991; 2010; Giles 2007a; 2012; Gwilt 2007).

The chronological understanding of the Iron Age has been driven by artefact typologies drawn from connections to prestige metalwork of continental types or with direct connection to these types. It has not yet been possible to completely connect the chronology of the Iron Age to calendar dates for two reasons. Firstly coinage only appears in the later Iron Age and limited to the south east of England. Imported artefacts which have closer chronologies are still limited by the possibility of curation (Cunliffe 2005, 32). Secondly scientific dating is seen as highly problematic for much of this period, radiocarbon dating

is hampered by the Halstattian plateau which limits resolution to around 400 years (Herve *et al*, in press). Archaeomagnetic dating is limited by the need for very specific samples and a calibration curve has only recently been made possible (Clelland in Lewis *et al* 2013; Herve *et al*, in press). Dendrochronology has the potential for accurate dating with tree ring records from bog oaks through this period, however it requires exceptional usually waterlogged preservation to have a large enough cross section to make the method possible (Bailie 1982). Therefore, archaeologists still tend to rely on artefactual evidence to date sites in this period.

The spatial division of the Iron Age has had a tendency to shape interpretation (Hill 1995a, 48) and innovations have been considered to filter from south to north (Hingley 1995). Often studies have leant towards the land and not considered the maritime element (Wilkes 2004, 33-34). The south eastern area of Britain and Wessex have been the limited portion of Britain where the idea of a 'typical' set of Iron Age features were based upon (Hamilton 2007, 82). Partially this is because this area was the main focus of excavations but also the sites in this area have generally had more elements of material culture surviving (Haselgrove 2003). The north and west of Britain are not completely devoid of remains and they may well have had a similar level of wealth to the south east as shown by the presence (albeit less frequent) of prestigious items. The wealth of this region may also have been displayed in less durable organic objects which have not survived (Cunliffe 2005, 82). The spatial division of Britain which although a defining factor in the early and middle Iron Age becomes a crucial division in the late Iron Age through into the period of Romanisation (Davis 2015, 36). The north western region showed a remarkable resilience to continental influence in the second half of the 1st century BC (Davis 2015, 30). The south east however appears to have had strong internal impetus for social change from the middle to late Iron Age. Traditional ties of kinship and shared beliefs in communities were

being shed for a move towards personal power, land ownership and importance of ancestry and individualism (Davis 2015, 30). These changes appear to have paved the way for the later acceptance of Roman practices and rule and contrast with the northern and western regions where conflict remained bitter and protracted (Hill 2007, 16-40).

If one region can be considered as the most influential in the study of the Iron Age it must be Wessex. It has been historically well excavated and surveyed and as well as the monumental hillforts of Danebury (Cunliffe 1984; Cunliffe and Poole 1991) and Maiden Castle (Sharples 1991) there are also well preserved settlement sites such as Gussage All Saints, Winnal Down and Little Woodbury (Wainwright 1979; Fasham 1985; Bursu 1940). The geology of this area means that as well as structures and artefacts bone and environmental data is well preserved as well, this has allowed for in depth studies into the communities and the social relations within them (Sharples 2010). The large developed hillforts of this area dominated this area through the middle Iron Age (Cunliffe 2000, 166). The scale of the enlarged ramparts means that they must have been time consuming and labour intensive to construct and to maintain. This work created 'physical links between the landscape, its inhabitants and the monuments' (Sharples 2010, 118). Settlement sites in this area became type sites and produced the 'typical' assemblages of Iron Age Britain.

Changes in society appear to have been mirrored in how settlements changed in this period. Giles (2007a) showed that the clustering and repeated rebuilding of roundhouses on the same spot was an 'act to remind people of the households association with a particular place' (Giles 2007a, 240). These settlements were marked out more significantly in the landscape with few formalised entrances and boundaries in contrast to the previous more open settlement. These clusters, she suggests, express society concentrating on kinship and family rather than larger communities. And that in itself implies that the ownership of land and the marking of territory show less reliance on community labour and mass storage of

crops (Giles 2007a; Moore 2006). In several areas the number of smaller settlements increased (Hill 2007; Giles 2007a), land previously less inhabited became used for settlement (Davies 1996; Hill 2007; Moore 2006) and the appearance of oppida. These were all attributed by Hill (1995a, 61-2) to be the result of a population increase leading to expansion and increasing permanence. Those willing to move to the less inhabited land may even have been more open to agricultural innovation and specialist craft activities (Davies 2015, 31).

Chronology of the Iron Age

The change that occurs throughout the Iron age has to be considered within its temporal depth as a crucial aspect of the period. A legacy of Three-Age system is the tendency to separate the stages in this system and therefore to fail to recognise differences within them. This static tendency is not universal but those accounts which do discuss change often offer simple interpretations of increased complexity through time. Alongside this the transforming effect of the withdrawal and resumption of long-distance exchange. This may work for regional trajectories but they do not work when applied, as they all too often have been, to the British Isles as a whole. Since the emergence of Iron Age archaeology in the 1930's the British Iron Age was divided into three periods based on pottery typology, the Early (c.700-450BC), Middle (c.450-100BC) and the Late (c.100BC-AD43) (Hill 1995a, 48; Cunliffe 2005, 32). This simple scheme is easily applicable but it has in-built biases and issues, it may be said this three way division is too different from the Halstatt and La Tene periods of the continent. These periods were set by metalwork types and these are rarely deposited in settlement contexts and as there are few graves in Britain establishing links is difficult. The appearance of coinage in the Late Iron Age can be used to provide calendrical dating but distribution is limited and coins only appear in the final century of

the 1st millennium, too rare to be truly useful to develop a chronology. Absolute scientific dating techniques could help to address issues with chronology but there are significant issues with the dating methods applicable to this period. Radiocarbon dating organic material is severely hampered by a 'plateau' (in reality a series of wiggles) in the calibration curve which at best gives a wide error range and at worst a spread of different dates all equally likely (Cunliffe 2005, 31). However, if applied correctly with subsequent analysis of the dates it still can play a crucial role (Garrow *et al* 2009) and can help resolve ceramic typologies (Hill 1995a, 75). Part of the reason why it has not been more widely used and is almost looked down upon is because it cannot give a finer chronology than existing ceramic typologies. Archaeomagnetic dating is also limited in accuracy because of its calibration curve, however unlike radiocarbon dating this curve can be improved with further application of this method (Clelland in Lewis *et al* 2013; pers comm). It is also limited by the availability of material it can be applied to. Dendrochronology is also limited by availability of suitable material to date, it has the potential for extreme accuracy (Cunliffe 2005, 31) but without a large enough well-preserved piece of wood it is not possible. However, it is only through radiocarbon and other absolute dating techniques that a chronology can be established across Britain (Hill 1995, 76). Standard chronologies are based on pottery, which is not found evenly across Britain, nor in universal forms which can correlate between locations. Where pottery is available in larger quantities it is relied upon for dating, the refined chronology of Wessex (Brown 1984) is very much the exception rather than the norm. Further confusion arises from the heterogeneity of phasing of the Iron Age, while some researchers see that there are as many as five (Cunliffe 2005) phases to the period some see it only as three (Hill 1995a) and some have even reduced it to two phases (Haselgrove and Pope 2007; Haselgrove and Moore 2007). These are the

heart of a chronological debate which has at its core the connections to Europe (Garrow *et al* 2009, 81).

An important factor to consider during the discussion of chronology is the importance of temporality from the viewpoint of the inhabitants of Iron Age Britain. The dominant activity at this time was the production and management of agricultural resources, this meant that the calendar year was dominated by when these processes needed to be carried out. This may have had the result of a circular calendar driven by seasonality. Outside of purely agricultural jobs other activities had to be carried out at certain times in the year to fall within the cycle as discussed below. This agricultural focus extended to be a key part of the cosmology of this period (Fitzpatrick 1997, 74-75). The circular nature of the agricultural year and the passing of the seasons can be seen to be reflected in the underlying cosmology of Britain during the Iron Age. This cosmology is seen in the dominance of circular houses across Britain before and during the Iron Age and even into the Romano-British period.

Landscape and Settlement

It can be said that Britain has the largest database of large scale excavations of widely studied first millennium BC settlements than any other European country (Cunliffe 2005, 20; Sharples, 2010, 1). The British Iron Age was a changing landscape of settlement from farmsteads and open settlements to enclosed developed agglomerations approaching something of an urban scale. The key element throughout this period however was the individual household and while there was variation in settlement pattern and structure across Britain the single household unit still dominated (Hill 1995a, 54). Settlements have come to dominate Iron Age studies as they are the closest to universal aspect of the archaeological record from this period (Haselgrove 2003). The excavation and detailed analysis of individual sites and settlements means that the Iron Age is dominated by site

types and type sites (Hingley 1984, 73). Despite the prominence of settlement in Iron Age studies the only region where complete landscapes have been studied for a significant length of time is the upper Thames valley (Hey 2007; Morrison 2015). Gravel extraction in this region since the 19th century means that the focus has been away from individual sites and more towards a wider landscape with a tradition of environmental archaeology and a focus on the sites place in the landscape (Hey 2007, 156).

Settlements have also been identified as an important focus for ritual activities such as feasting and ritual deposition (Hill 1995a, 54) and craft activities such as metal working (Collard *et al* 2006; Henderson 1991).

The landscape in which these settlements sat was man-made, open and agricultural (Robinson 1984, 1) with isolated patches of woodland left in areas less suitable for crop cultivation. For example the clay filled river valleys cutting through the chalk downs or the clay-with-flints topped hills (Sharples 2010, 23). Studies in Wessex and the Thames Valley have shown that both of these regions would have been largely if not entirely cleared of woodland (Robinson 1984, 4; Thomas *et al* in prep).

Finds recovered from these sites although they may often come from structured deposits, still show that agricultural, craft and domestic activities were carried out on settlements. The few activities which were carried out beyond the settlement boundary were either due to the practical location of the resource availability (Hill 2007, 22) or because they may have been taboo (Hingley 1997, 12).

The archaeological record is biased toward enclosed sites due to their greater visibility and as in certain regions and certain periods unenclosed settlement was more typical, unenclosed settlements are less well understood (Hill 1995a, 58). As the Iron Age progressed the trend was for settlements to become more enclosed, this pattern is true for

all sizes of settlement from individual houses set within fields to tightly clustered agglomerated settlements. These agglomerated settlements may have been most common in central and eastern England but they were found elsewhere. They were often not the only settlement form in an area and could have been contemporary with smaller enclosed settlements (Hill 1995a, 59). Settlement size and form appear to be the products and producers of local social forms not the product of environment or economy (Hill 1995a, 59; Hingley 1984; 1995). For example, despite similarities in general setting during the middle and late Iron Age in the Thames valley open settlements were common and in other major river valleys such as the Severn and Avon enclosed settlements were dominant (Hill 1995a, 59).

Within the settlement patterns of the Iron Age there have often been considered to be central places, with the most synonymous of these being the Hillfort. Enclosures surrounded by an earthen or stone wall, they have been interpreted as towns, fortresses, gathering places and finally as being potentially all of these across the country at different times (Hill 1995a, 67). Hillforts are not the universal entity they once were considered to be. Interestingly they do not generally occur in the same locations as deposits of weaponry in graves or hoards (Hill 1995a, 69).

In the late Iron Age the appearance of *oppida* as a central place is a noticeable change, as large enclosed settlement sites which almost equate to urban centres (Hill 1995a, 70). These sites stand out as being primarily settlements, located often in areas poor for arable agriculture but, possibly importantly, in land suitable for feeding and watering livestock (Davis 2015, 34). Creighton (2000) sees these sites as being the sign of a change in social control, ‘Perhaps we might be moving away from our egalitarian hillforts and towards a landscape managed, ruled and terrorised by new leaders with faithful followings’ (Creighton 2000, 17). These sites have significance not only for their size but also as high

status settlement, widespread burial and the consumption of continental material. Megaw and Simpson (1979, 374-9) saw *oppida* as being associated with activities such as manufacture and trade rather than agriculture. There are further sites which although they are unenclosed would also fit into the category of a large agglomerated settlement with extensive contacts for long-distance exchange, craft and wealth (Hill 1995a, 72; Davies 1996, 78). These sites have been considered as being evidence for continent influence across southern England. Their location in peripheral areas, at the junction of rivers, (Davies 1996, 78) on poor arable land best suited for animals (Creighton 2000) and away from existing power centres such as hillforts (Moore 2006, 151) has been suggested to be the result of their formation by groups peripheral to existing society. They were 'developing their own dynamic, leading to radical social developments' (Moore 2006, 151).

With wide scale study of settlement and landscape have been dominant the study of material culture has become neglected (Deroche 1997, 82; Haselgrove and Moore 2007, 7).

Specialist scientific contributions into Iron Age studies have led to artificial compartmentalism of Iron Age life. The number of individuals engaged in any specialised practices would have been limited and all activities would have been carried out within the agricultural year. Across Britain the economies of individual households were aiming to produce a surplus to compete with other household and for social influence. How these surpluses were consumed were led by the social norms which were enacted and reinforced through ritual behaviours. The exploitation of plants for food, fuel, fodder or building materials was key throughout this period. (Jones 1995). Mixed farming did take place across Britain but the importance of plant and animal products and particular species varied in space and time. The archaeological evidence suggests that cereal crops dominated to an

extent not seen before or after. As the 1st Millennium progressed there was an intensification of land use and resource utilization and expansion of settlement into landscapes which were previously only episodically exploited. The result was a landscape which was densely populated at the time of the Roman arrival (Hill 1995a, 61). These agricultural intensifications were accompanied by new technologies, animal and plant species. While it is clear that households would have focussed on the land close to or surrounding their settlement temporary seasonal movements for animal grazing or exploiting resources such as sea salt, stone for querns and possibly even metal (Hill 1995a, 61).

Craft and Industry in the Iron Age

The craft processes being carried out in this period were inextricably linked with the agricultural regime but they also show a similar picture of diversity. The evidence has been regarded as showing that there is a general trend of increasing production and specialisation (Hill 1995a, 62) Since these overarching summaries of the period have been carried out however there is growing evidence for higher levels of production earlier in the Iron Age suggesting that there is a flatter or even level trajectory (Halkon 1997; Preston 2013). The metalworkers of the Iron Age identified and exploited a range of ore sources from across Britain (Hill 1995a, 62). Salter and Ehrenreich (1984) postulated that there was a hierarchy of metalworkers based on their skills and that the individual techniques they possessed were tightly controlled. The presence of iron smithing slag on most settlements indicates that iron working was to some extent widely disseminated. Ore extraction was however more limited simply because of ore distribution, however it appears that the distribution of exploitable ores is not as limited as has been suggested; especially when tertiary ores are considered (Preston 2013; Youngs 2010; Paynter 2006). Where metalworking evidence is found it is often limited and considered to be small scale and short term (Hill 1995a, 63).

The same has been considered for other crafts such as pottery production, quern stone production, glass, shale and salt (Hill 1995; Henderson 1991; Morris 1994). There is some evidence however for increasing social complexity with these materials as they were traded and exchanged over greater distances during this period. Individual centres of production became more dominant, such as the Poole Harbour pottery industry. It is difficult to examine whether organic materials such as wood or textile were traded over these similar distances and impossible to determine to what extent other even more ephemeral commodities such as animals, people and knowledge moved around the landscape.

As the agricultural calendar to a large extent controlled the distribution of labour resources other activities including craft and industrial processes would have to fit around it. The winter is suggested to be the time when craft and industrial processes could take place as manpower was freed up from working in the field (Fitzpatrick 1997, 74-75). But obtaining the raw materials required for these craft activities would have also had to fit into this calendar. For example work in wetland areas, collecting roofing material or bog ore would have been carried out during the summer when the water level would be at its lowest and the wetland the most accessible. Collecting wood for construction or fuel would have to be carried out in the autumn or winter when trees are dormant and there was a reduction in undergrowth which would make access easier. Iron smithing is one of the few activities which could have been carried out and would have needed to be carried out throughout the year. Smelting on the other hand would have a more limited window in the year as it required a larger supply of labour as well as suitable dry fuel (Giles 2007b, 398).

Metalworking as one element of the economy of the Iron Age required a series of raw materials and labour to ensure successful operation. The production of metal requires the metalliferous ore, fuel, a vessel to contain the reaction and labour to carry out the process, it is also likely to have required ritual materials (Hingley 1997, 9; Herbert 1993). Each of

these would likely be found in a different location and have to be recovered at different times of the year, this indicates that even the smallest operation would have required significant planning. There is substantial evidence, in the form of large deposits of slag for the production of iron. However, there is very little archaeological evidence for ritual activity identified on smelting sites. However, a review of this has suggested that it is present but has been missed, with evidence from Bryn Y Castell and Crawcwellt in the form of placed deposits including hammerstones while at Brooklands one of the furnaces excavated was reinforced with a sherd of pottery (Hingley 1997, 11). Metalworking activity has often been located at the periphery of settlements (Hingley 1997, 12), this has been suggested to be for safety purposes (Cleere in Hanworth and Tomalin 1977; Henderson in Sharples 1992). But there is evidence for the location of metalworking on settlement sites and the possible connection with social control of metalworking (Hingley 1997, 12). Iron smithing in particular has a connection with settlements and even a connection with cosmology with the evidence for it in the south eastern boundaries. Henderson (Sharples 1992) also suggests that metalworkers were ostracised as unclean and of a low status and forced to the periphery of settlements. Contrary to this metalworkers were noted as being high status in the study of Early Historical Ireland and ethnographic studies in Africa (Gilles 1981; Herbert 1993). Other ethnographic studies (Rowlands 1971) have shown that there is not necessarily a hierarchical relationship between a smith and the wider society (Giles 2007b, 397). The extent of craft specialisation in the middle to late Iron Age is crucial factor to understanding wider social organisation. Craft specialisation would only be possible if there was an agricultural surplus, a society with this level of surplus would also have the possibility of maintaining permanent military forces and religious elites (Giles 2007b, 397). Achieving an agricultural surplus would have made more possible with quality iron tools. Once a surplus was achieved a chiefs authority could

be underpinned by the smiths ability to produce iron weapons and high status objects (Giles 2007b, 397).

Hingley (1997) and Giles (2007b) discuss the connection between iron production and agriculture during the Iron Age. The digging for sub-surface deposits of ore would have involved actions and implements similar to those for agricultural processes or for bog ore the gathering of peat for fuel (Giles 2007b, 400). The processing of ore has similarities with the processing of grain, with pounding, sorting, washing and grinding of ore comparable to the cleaning, winnowing and grinding of grain (Hingley 1997, 10). African groups have drawn analogies between grinding ore and grain or other staples, with similar implements used to fulfil these different processes (Herbert 1993, 30). Quernstones normally associated with grain were used for grinding ore (Williams 2003, 233; Giles 2007b, 400). The roasting of ore can be seen as a parallel for the parching or drying of grain. That craft and industrial activity would have been isolated from ritual and cosmology is a very modern view, ethnographically it is known that smelting was intrinsically linked with reproduction (Herbert 1993, 20; Haaland 2004, 8) and agriculture (Herbert 1993, 30).

Ritual activity

The ritual activity of the Iron Age is difficult to determine as it is a period lacking the monumentality of the preceding Neolithic and Bronze Age and without consistent evidence for the treatment of the dead. The evidence available is varied in quantity and quality across Britain (Cunliffe 2005, 543). Ritualised acts would have been part of a complex belief system pervading everyday life (Cunliffe 2005, 543), the challenge for archaeologists is how to identify the evidence left to us. While there is limited evidence for ritual in the Iron Age there are some examples of the connection between iron and ritual activity from this period.

Burial rituals

It is frequently suggested that there is little trace of Iron Age burials, and when compared to continental Europe this may well be the case. However, when the evidence is brought together there is a well-defined series of ritual practices which can be shown to change over time (Cunliffe 2005, 543). The early Iron Age has some evidence for cremation burial continuing through from the late Bronze Age, however the lack of grave goods or pottery containers mean that these would have to be radiocarbon dated to confirm an Iron Age rather than Bronze Age date (Cunliffe 2005, 544). Inhumations are much rarer this early but become more common from the 5th century onwards, however the practices still vary considerably across Britain; cemeteries of cist burials in the west, barrow cemeteries in Yorkshire and excarnation and subsequent burial in the central south for example (Cunliffe 2005, 544-559). In the south east from the beginning of the 1st century BC urned cremations cemeteries became increasingly common (Cunliffe 2005, 559). Over this regional and chronological patterning was a separate pattern indicating the social position of the deceased (Cunliffe 2005, 561). The Rudston burial, an inhumation with ironworking tools provides one of the few examples of an individual being directly connected with ironworking (Stead 1991). The identification of a smelter from their grave goods may be more difficult without remarkable preservation of their tools.

Structured deposition

The phenomenon of structured deposition (Hill 1995b) or propitiatory offerings (Cunliffe 1992), when correctly identified as such rather than natural formation processes or indiscriminate deposition, is a very useful tool to comprehend ritual in this period (Giles 2007b, 395). The placement of seemingly casual refuse in disused storage pits does not seem to be as straightforward with the identification of consistent behaviour this could be recognised as a ritual deposit (Cunliffe 2005, 570). The evidence from Danebury and

contemporary sites for example shows that complex patterns of deposition took place involving whole or partial animal and human carcasses, sets of pots and groups of other artefacts likely including organic material which does not survive (Cunliffe 2005, 570). The deposition of metalworking objects with grain at Garton Slack shows a connection between metalworking and agriculture, this careful deliberate placement may have been to appeal to the forces of fertility (Giles 2007b, 402). There was however evidence for ritual activity in the form of structured deposits of domestic material and damaged objects, often located in settlements (Hill 1995a). The pattern of distribution of metal artefacts changed from the Bronze Age away from bronze objects in watery places to deposition of iron in dry locations such as settlements and hillforts. This increased in the later Iron Age but the deposition was not consistent with clusters and sparse areas. Towards the end of the Iron Age more visible mortuary practices and shrines appeared, these can be seen as a change from the predominant domestic focus of the preceding centuries (Hill 1995a, 66). Iron currency bars are often deposited at settlement boundaries (Hingley 1990), while at Danebury iron hoards were placed underneath houses (Cunliffe 1995, 86) a possible attempt to ensure the well being of the occupants. The deposition of currency bars has been well discussed (Crew 1994) their deposition reflects the importance of raw iron metal as well as finished iron artefacts.

While religious and ritual locations have been identified in the Iron Age, consisting of natural locations such as springs or clumps of trees or artificial structures (Cunliffe 2005, 561). They are few in number and their connection to the production of iron has yet to be established.

Two broad categories of Iron Age ritual foci can be identified, shrines consisting of an artificial structure and natural locations such as springs or clumps of trees (Cunliffe 2005, 561). Many of the pieces of elaborate metalwork recovered from wet places may well have

been offerings deliberately dedicated to the spirits of that place (Fitzpatrick 1984; Cunliffe 2005, 566). When found these deposits can be remarkable in both quality and quantity suggesting a high percentage of a society's wealth was tied up in these dedications (Cunliffe 2005, 567).

Boundaries, especially those defining settlement or habitation area also seem to have had a ritual significance, and the creation and maintenance as such will also be embedded in ritual (Hingley 2006). The entrance of an enclosure, as it marks the point of transition from outside to inside would have been of particular focus and may have been subject to taboos (Cunliffe 2005, 576). Deposits made in these locations may well have had special significance, and activities carried out in these areas may show the taboos concurrent with these activities (Cunliffe 2005, 577-578).

Social Organisation

The interpretation of Iron Age social organisation has been the subject of intense debate, key among this has been the move away from the idea of a Celtic or Iron Age society to more specific interpretations which fit better the varied archaeological evidence. This has been accompanied with the discussion of to what extent were Iron Age societies hierarchical and an emphasis on the household and as a basic unit of society and with the spatial organisation of society as integral (Hill 1995a, 73). The traditional models have generalised links to a warrior based hierarchical society from classical writing and analogy to the Irish medieval heroic literature, this connection has been much debated. The discussion of hillforts by Cunliffe being an example of the combination of this with processual social archaeology, showing evidence for an elite led group with centralised powerbases illustrated with the core-periphery model. These show society as having a hierarchy organised around competitive relation between and within lineages or clan groups. Further approaches have moved away from these generalising viewpoints on the

period. They have recognized that no single form of the British Iron Age really existed and that the archaeological evidence demonstrates differences in the way the communities were organised and the material resources affected them (Hill 1995a, 73).

Closing remarks

The factors discussed above show that there was a complex diversity across Iron Age Britain and that it cannot be considered as a simple single entity. A progressive increase in population over this period appears to have been the pushing factor that led to many of the changes in settlement type and location in the second half of the Iron Age. These visible changes may also reflect a change in the social organisation, and may even show an increased influence of continental Europe. The causes for these changes and the ultimate results varied between regions but many of these changes were ultimately a response to an increasing population. Iron Age studies have been heavily focussed on the occupation of landscapes, structures and structured deposition. The Iron Age was not homogenous, there were variations in material culture, settlement and social and culture differences both spatially and temporally. This variation has also been caused by the heterogeneity of the study into it.

The evidence for Iron Age iron smelting

The evidence for Iron Age iron smelting has been limited for much of the last century with few sites of this period being identified correctly. The early 20th century saw excavations at All Canning's Cross (Cunnington 1923), Trevelgue Head (Nowakowski *et al* 2011) and Brooklands (Hanworth, Tomalin 1977) all revealing iron smelting being carried out on settlement sites. It was not until the end of the 20th century that sites such as Bryn-Y-Castell and Crawcwellt in North Wales (Crew 1995) and East Yorkshire (Halkon 1997) were excavated, these sites contained much larger quantities of slag (1000s rather than 100s of kilograms of material). Into the 21st century further sites have been identified with large

assemblages of slag as well as being more geographically diverse such as Sindlesham, Berkshire (Lewis *et al.* 2013) and Messingham Quarry, Lincolnshire (Pitts 2016).

The presence of slag at sites from this period has been too often oversimplified to 'ironworking' or even 'metalworking' with resulting assumptions that this is iron smelting. The hillforts of Wessex and the Glastonbury Lake Village have been cases of this occurrence where iron smithing slag has dominated the assemblage but statements asserting iron production have been made. Hengistbury Head is another example of a site which has the reputation of being a key iron smelting site for this period. A series of iron smelting furnaces were excavated in the early 20th century (Cunliffe, 1979) but they were not able to be dated at the time. The presence of roasted iron ore in Iron Age contexts had also been given as evidence for iron smelting. However, Salter in the excavation report suggests that this material was not smelted on this site and was either traded off site or used as either a pigment or a polishing matrix (Salter in Cunliffe 1987, 197). It is likely that Hengistbury Head was the site of Iron Age iron smelting but the current evidence cannot support this as the iron smelting that was identified has not been dated and the ore recovered from Iron Age contexts on this site does not necessarily have a direct relationship with iron smelting (Salter in Cunliffe 1987, 197).

The excavations carried out at All Cannings Cross (Cunnington 1923) were amongst the earliest dated evidence for Iron Age smelting, allocated to the La Tene I period, slag was recovered from a number of pits across the site, some of which was considered consistent with tapped slag (Cunnington 1923, 199). This slag was considered to have flown between chalk blocks placed at the top of a pit, suggesting something possibly similar to a slag pit furnace. The ore was considered to be from the local greensand deposit located close to the site. The slag was examined microscopically and fayalite, magnetite and 'finely divided silica' were identified (Whiteley and Hallimond in Cunnington 1923, 53). Unfortunately

as this was excavated in the early 20th century the quality of recording and dissemination leaves much to be desired, 'All Canning's Cross is an old excavation not published to modern standards' (Cunliffe 1984, 18). Despite this it is an important site in wider Iron Age studies as the site where hematite coated bowls were found as an indication of the early Iron Age (Cunliffe 1984, 18). The excavated material from this site has been located for reanalysis as part of this thesis and will be studied and discussed later.

The smelting evidence found at Brooklands in Surrey was for a long period one of the most well known iron smelting sites from the Iron Age. The scale of production at this site was initially suggested to have been 200kg of finished iron (Cleere in Hanworth and Tomalin 1977), but a reassessment of the results showed that from the slag recovered that possibly as little as 2kg was produced (Salter, Ehrenreich 1984). It would seem that the amount of iron produced would in fact be between these two values. In any case the smelting activity on this seem appears to have been an infrequent and limited scale event.

Trevelgue Head on the north coast of Cornwall was excavated in the late 1930's but was only anecdotally reported in public lectures by its excavator C.K Croft Andrew (Nowakowski, Quinnell 2011, 47). Only 70 years after its excavation was it finally published and the slag held as part of the archive was finally analysed. This showed that only iron smelting and not iron smithing was carried out on this site and that the highly contentious bowl furnace was likely to have been used successfully. This exposed headland was home to a lode of ore, which could have been be mined directly from the cliff face below the site.

When compared to these earlier excavated sites the Iron Age smelting sites of North Wales excavated by Peter Crew in the 1980's and 1990's are enormous (Crew 1986; 1989). The recovery of 1200kgs of slag from Bryn Y Castell and 6000kg from within structures at

Crawcwellt, possibly the by-product of the production of 100kg and 500kg of iron respectively indicate that the production of iron in the Iron Age was not solely a small scale craft like it had been considered. These sites are also very important for the extra data which has been made possible through the use of complimentary fields of archaeology, such as environmental archaeology (Mighall, Chambers 1989; Chambers, Lageard 1993; Crew, Mighall 2009) archaeomagnetic dating and geophysics (Crew 2002). These have given vital insights into the impact of iron smelting on the wider landscape.

Peter Halkon's work (Halkon, Millet 1999; Halkon, Starley 2011) in Yorkshire revealed again that large scale iron smelting was being carried out in Iron Age Britain and that the sites from North Wales were not unique, although they were still considered to be exceptional (Slater 2012, 25). The evidence for a number of sites, connected by possible transport links to each other and possibly to the wider area had not previously been seen in British Iron Age iron production and with the site of Welham Bridge the title of largest slag heap changed hands.

While these sites were generally found on research excavations the next step in the increase in Iron Age smelting sites was due to widespread commercial archaeology and in particular associated with the extraction of gravel and sand. Hartshill Copse, perhaps better known for the claims of the earliest iron working in Britain (Collard *et al* 2006) also produced evidence for iron smelting in the late Iron Age (Brett *et al* 2004). Another site with claims to Late Bronze Age iron, this time in the form of smelting was Messingham Quarry, in-situ furnaces were found during the excavation of evaluation trenches in advance of sand extraction with a radiocarbon date placing the furnace in the between 950 and 800 BC (Pitts 2016, 6). While this date was later shown to be too early later excavation on this site has still produced furnaces of potentially early Iron Age dates (Pitts, 2016, 7). The scale of production on this site is still unclear as excavation work has not yet been reported upon

at this time but anecdotal reports of extant banks of slag around the field as a result of ploughing (Pouncett *pers comm*) suggest that a substantial amount of iron may have been produced at this site.

The analysis of the slag from the early phases of Hartshill Copse was carried out by Dr Tim Young of GeoArch (Young 2003; 2004a; 2005), as part of his consultancy work he has analysed the slag and identified smelting from over a number of Iron Age and later sites sites in Britain and Ireland. The spread of his work has shown that iron production was carried out across much of southern Britain with evidence from Cornwall to Kent and Hampshire to Herefordshire.

As well as Hartshill Copse a number of other Iron Age iron smelting sites have been found in the south of Berkshire, north of Hampshire and west of Surrey (Preston 2013; Youngs 2010; Dungworth 2007; Starley 1998). These sites, including those sampled as part of this thesis form an important cluster of sites located close to the confluence of the Rivers Kennet and Thames.

An important factor to consider at this stage is that all of these sites were found outside of the three regions which dominated iron production leading onwards. Although there are Iron Age sites in the Weald and the Jurassic Ridge of Northamptonshire they tend to be late often overlapping through into the Roman/Romano-British period. There are no sites confidently dated to the Iron Age from the Forest of Dean (Hoyle *et al* 2007, 85).

As discussed earlier identification of ritual on iron smelting sites can be difficult, to this date the best evidence is from the North Wales sites. The inclusion of slag in structured deposits may be an indication of the symbolic power of iron and also the smelter. Identification of this may be difficult unless the remainder of the deposit is also preserved and actually sampled for.

The evidence for Iron Age iron smelting has changed dramatically over the last 20-30 years in Britain. The prevalence of commercial archaeology has led to an increase in number of Iron Age iron smelting sites being identified from this period. The discovery of these sites mean that the existing views of iron smelting need to be reassessed. Regional and national syntheses of the Iron Age still do not account for these new sites. As well as the location of these sites their scale and nature mean that sites excavated without the use of modern methods and poorly disseminated do not have to dominate the discussion of this period as they have been. It is true that many of these sites have not made a greater impact on wider Iron Age studies because they have too often only released as grey literature. It is also unfortunate that the focus on published sites has been on exceptional sites rather than general trends. It is also important to acknowledge that iron smelting has to be clearly identified rather than assumed from an incomplete record. As discussed by Salter (in Cunliffe 1987) metallic ores have other functions aside from a raw material for smelting. The role of metallic ores as pigments is well known and their roasting for pigment production has been suggested as the origin for extractive metallurgy. Slag may have had a further ritual role which has not been identified, it has been noted as having a medicinal role in India (Lahiri 1995, 129) and with iron likely to have been part of a wider regenerative cosmology slag could also have been a powerful ritual material in the Iron Age.

The appearance of iron in the archaeological record is not as a production industry or in the form of new artefact types, it is within hoards of bronze objects as skeuomorphs of existing bronze objects (Hill 1995a, 77).

2.3.2 Iron Age to Roman Transition

The transition from the prehistoric/protohistoric, alien, otherworldly Iron Age to the historic, identifiable Roman period is an important transition in British archaeology (Johnson 1997, 308-309). The idea of Romanisation has changed significantly, but there is much that is still not understood (Morrison 2015, 1). Even the meaning of the term Romanisation has changed much since its conception in the early 20th century (Webster 2001, 209). In the attempt to understanding various aspects of the late Iron Age a vast amount of work has been produced, however none of it adequately addresses the issue of why different Iron Age societies adopted different aspects of the Roman way and at different rates (Morrison 2015, 7). The concept of Romanisation as first defined is too simplistic, an outmoded model of acculturation (Webster 2001, 209). The idea of Romanisation changed during the course of the 20th century and despite the best wishes of those who would redevelop the concept it remained a one sided theory – *ROMAN*isation (Webster 2001). It remained as the idea of civilising non-Romans, giving them a uniform language, art, architecture and religion, the spreading of *humanitas* and instituting of the *Pax Romana* (Webster 2001, 210). The role of the native in the adoption of Roman ways was considered largely secondary until the emergence of a nativist counterapproach in the 1970s and 1980s (Reece 1980). They considered that Romanisation was little more than the a surface gloss beneath which native life remained unscathed alongside Roman life; the Roman way was neither embraced nor resisted but largely ignored (Webster 2001, 211). The idea of the arriving Romans civilising the Britons stood until the late 20th century, new theories in the 21st century have been focussed on a more nuanced scheme of adoption by the native population (Revell 2009; Mattingly 2006; Morrison 2015, 17).

The commencement of the Roman period has been traditionally defined as AD 43, the date of the successful invasion of the south coast of Britain by Claudius. Even if we consider this to be the case then the period of conquest took several decades, leading to a series of frontier lines and the impact of the Empire began before the conquest (Rogers 2015, 8; Creighton 2006). Realistically it could be said that the Roman period could be defined as when Roman artefacts begin to appear in the archaeological record (Morrison 2015, 18). The growing influence of Rome began once it became a direct neighbour during the 1st century BC. The Gallic Wars brought the Mediterranean power to northern Europe and through their records our understanding of the people and landscape of Iron Age Britain was first shaped. The idea of the Celtic warrior and the warrior-led hierarchy are a direct result of the Roman accounts (Rogers 2015, 10; Hingley 2011, 617). Gardner (2001, 36) states that change does not happen simply at the interaction but carries on throughout the Roman period and even beyond.

The discovery of greater numbers of 'continental' artefacts in Iron Age contexts demonstrates greater contact with continental Europe. While the appearance of coinage is a clear and dateable indication of the interaction between Britain and Europe, it is much more difficult to understand why this change occurs (Cunliffe 2005, 125-126), especially given the history of contact with the continent. Trade had been passing between Britain and the continent for millennia, in the late Iron Age this becomes a movement of ideas and people as well as objects, and these people were relocating further inland (Morrison 2015, 14).

It has to be recognised that sweeping generalisations of Romanisation can no longer be applicable; given the amount of new information the late Iron Age of southern Britain cannot be understood as one homogeneous entity but only by studying it at a local or sub regional level (Morrison 2015, 14). This also applies to the adoption of Roman ways,

different groups appear to have had greater or lesser resistance or inertia to adopting new material culture and lifestyle (Morrison 2015, 7).

2.3.3 Roman iron production

If one material was crucial to the Roman Imperial economy is must have been iron; without this it would not have been possible to arm its legions, cut the stone for its public works or produce and harvest the grain which fed its population. The evidence for the exploitation of metals has been preserved in the distant ice sheet of Greenland, at a level which was not matched until the Industrial Revolution (McConnell and Wilson 2017; Fleming 2012, 6). The mineral wealth of Britain was discussed by Roman writers Julius Caesar and Strabo, who both discuss the amount of metal available in Britain, although they have differing opinions on the scale of iron production (Nicodemi 2004, 115; Caesar V, 12; Strabo IV, 99). Iron and steel played a key role in the Roman world from arming its legions to creating its artwork (Sim and Ridge 2002, 17). It is hard to find a manufacturing process which did not rely on iron at some stage (Sim and Ridge 2002, 18). The consequences of the capacity to produce such large amounts of metal were not only the ubiquity of metal goods but also affordability and availability (Fleming 2012, 9). The Roman military was a key consumer of iron, with approximately 38 tonnes of iron required to fit out a single Roman legion (Nicodemi 2004, 114). It has been estimated that on average, 1.5kg of iron was used per person per year in Roman Britain. Therefore, with a conservatively estimated population of 1.5 million in Britain, 2250 tonnes of iron were required per year (Aiano 1970). Other estimates of the population of Roman Britain extend up to 3.6 million, requiring 5400 tonnes of iron (Millet 1990, 185). Using this figure and experimental studies it is possible to estimate the raw materials required: 93,750 tonnes of ore and 112,500 tonnes of charcoal (Crew 1998, 51). This volume of charcoal would be the equivalent of 787,500 tonnes of raw wood (Cleere 1976, 240). Sim (1995, 393) has calculated that it would have required

a workforce of 50,000 for the smelting and bloomsmithing processes alone. With the associated mining of the ore, harvesting of trees and production of charcoal, transportation of the various raw materials and the final product and the administration of all of these would have required at least 150,000 people. The level of administration and organisation for an industry of such a size would have been significant within the province. The complex of institutions, materials and workers which lay behind the productivity of the iron industry can be shown by the Inchuthil nail hoard (Shirley 2000). Several tonnes of nails (almost 1 million individual nails in total) in various sizes and iron alloys were recovered. The iron is thought to have been brought to the site from the Weald, then smithed on site. The use of such a volume of iron on an individual site was not to be repeated until the large public buildings of the Middle Ages (Fleming 2012, 8). It seems likely that there was even an excess of iron in Roman Britain, with suggestions that the excess iron was exported to continental Europe and used to arm the legions located along the Rhine. There was enough fresh iron available so that recycling was not frequently practiced (Fleming 2012, 9).

Iron production took place across the Roman Empire with identified exploitation of iron in Spain, Gaul, Italy, Elba, Sardinia, Central Europe, Noricum, Illyria, Macedonia, Asia Minor and Africa (Healy 1978, 64-65). Steel was widely used, known about and recognised across the Roman world, but there was not a specific Latin word for it. The only definite mention of steel was carburising of raw iron, a production method which has high cost implications, as it would require being baked in a carbon rich atmosphere for a long period (Sim and Ridge 2002, 122).

The quality of material and workmanship in the equipment of the Roman legions in Britain has been shown to be exceptionally high (Fulford *et al.* 2004, 249). The iron which was used for the armour, for example, had low levels of slag inclusions and required a series of different methods of manufacture showing the quality of the iron and skill level of the

smiths. Evidence for annealing and hardening suggests that not only were the smiths skilled enough to identify metal which was suitable for these processes, but that there was enough control to be able to produce this material (Fulford *et al.* 2004, 248). The suggestion has been made that the skilled smiths were limited to the military and were focussed primarily on the production of weapons and armour. Fulford *et al.* (*ibid.*) use the example of iron beams found in bathhouses such as Catterick to support this argument. The beam from this site appears to have been made from a number of whole blooms, they have not been heavily processed and still contain a large number of slag inclusions (Starley 1997, 8). This was given as evidence for poor workmanship when compared to the quality of the arms and armour. This may reflect more on the sheer scale of the piece (c1.8m in length when complete), which would have made it very difficult to repeatedly transfer from hearth to anvil. The beam was also welded together in a herring bone pattern, overlapping blooms to strengthen the beam (Starley 1997, 8).

The Weald of Sussex and Kent has long been identified as an area which has been a key iron producing region. The geology of this area made it very well suited to the production of iron, the heavy clay natural substrate not only being suitable to construct furnaces from, but also containing patches of siderite ore (Cleere 1981, 67). The clay soil would have been difficult to plough until the introduction of mechanised ploughing equipment. Therefore, the area remained wooded providing the perfect combination of conditions to allow for the production of iron. Where streams cut through the beds of sand and clay, the ore would have been exposed in valley sides. Amongst the earliest examination of Roman smelting sites in Britain was conducted in the Weald of Sussex and Kent. This early work was initiated after Roman material was found in the slag heaps which were being mined for road material. The recovery of Roman coins within the material at Beauport Park led to further work on this site which led to the discovery and excavation of the bath house at this

site. The scale of the smelting operation at this site has been referred to repeatedly as evidence of vast production, but as yet there still have been no furnace remains discovered. The focus of the archaeological work at this site was the bath house, or a 'workers village' (Brodribb *et al.* 1988, 221). The scale of production at Beauport park and also Bardown is unprecedented in Britain outside of the Weald. These sites produced thousands of tonnes of iron over their lifespan resulting in the creation of hundreds of thousands of tonnes of slag. Within the Roman Weald roads close to concentrations of iron smelting were constructed using slag as a metalling material (Margary 1947; 1965; Cleere 1981, 67). By the end of the 1st century AD, most of the iron sites were located in the coastal area with some in the High Weald. In the 2nd century, more sites were established in the High Weald, including some of the largest sites; by the beginning 3rd century, the larger sites began to cease operating but associated satellite sites continued until the mid-3rd century, at which point most sites cease entirely (Cleere 1981, 66). The widespread smelting in this area recommenced during the medieval period, continuing through the progression to charcoal fuelled water powered blast furnaces. This area was recorded in historical documents as producing substantial quantities of iron. It was this which increased the interest in the area, leading to Straker's '*Wealden Iron'* (1931) which looks at the entire known history of Wealden iron production including the Roman sites. Straker's study was a crucial step towards further work in this region, highlighting the importance of the Weald as an iron production area in the past. The organisation of the iron industry in the Weald has been given as an example of the influence of the Roman empire. An inscription found in Chichester attributes the control of the iron industry in the Weald to a local king licensed to produce iron for his Roman masters. The death of this individual has been suggested as the key moment where the production of iron was shifted from a private venture to control by the military. The discovery of Classis Britannica tiles at the smelting site of Bardown

led to Sir Ian Richmond suggesting a military control of the smelting (Richmond 1963), further discoveries of stamped tiles led to Frere (1967) suggesting with less conviction there was some form of connection to the military. Cunliffe followed this claiming that 'It may well be that much of the Sussex iron industry was under official control by this time' (1968, 258).

The work of the Wealden Iron Research Group has led to the identification of over 100 Roman period sites identified and dated by either trial trenching or surface artefact recovery (Bayley *et al.* 2008, 45; WIRGdata 2017). The scale of production in the Weald varies massively with the largest sites being 3000 times the size of the smallest sites (Bayley *et al.* 2008, 45; Hodgkinson 1999). Some of these smaller sites are discussed as being satellite sites for the larger sites. The work which has been carried out in the Weald is a good example of what an integrated study of a Roman iron producing landscape can reveal (Bayley *et al.* 2008, 46).

The Forest of Dean was another major iron producing region throughout the Romano-British period and one of the three main iron producing regions of Roman Britain (Hoyle *et al.* 2007; Cleere and Crossley 1985; Schrüfer-Kolb 2004). The evidence for earlier Iron Age smelting in this area is limited, there are less than 5 sites were slag has been listed as an artefact on Iron Age sites. However, the slag has not been studied and connected to a process and represent smelting, smithing or both processes (Hoyle *et al.* 2007, 94). As well as these potential early sites, there are a number of sites within and immediately surrounding the Forest of Dean which have been identified as dating to the 1st century AD and which have produced slag (Walters 1992, 6). It has not been established which process generated much of the slag from these sites. There are two sites, at *Ariconium* (Weston under Penyard, Herefordshire) and Monmouth which have evidence for in-situ iron smelting dating to the 1st century AD (Hoyle *et al.* 2007, 95). The scale of the production

at Monmouth is unclear (Hoyle *et al.* 2007, 111) and appears to have been overestimated at *Ariconium* (Jackson 2012, 179). The details of the process and scale of production in the Forest of Dean in this earlier period have been unclear and it would not be possible to suggest the scale and organisation of the industry based on the available evidence (Hoyle *et al.* 2007, 111). A number of the sites are on small scale and may have been for immediate local need.

The iron industry in the Forest of Dean from the 1st to 4th centuries AD has long been discussed as operating under imperial control. The suggestion being that the area was an imperial estate dedicated to the exploitation of the local iron ore deposits (Hoyle *et al.* 2007, 111). As with the Weald it has been "generally accepted" that the mineral resources were state run in one form or another (Cleere and Crossley 1985, 66). In the 1st century AD Vespasian established a network of imperial estates which included the major metal production regions (Rosrovtzeff 1957, 110). Imperial control of mineral resources appears to have taken two forms, the first being the direct military control as evidenced by the Weald. The second was imperial responsibility but local administration (Cleere and Crossley 1985, 66-67). Evidence for both of these have been shown in Britain from the stamping of lead ingots from the 1st century AD lead industry. The complexity of the system is shown by an ingot with both imperial and private stamps (Salway 1993, 442). Even if the imperial model postulated for the Weald is accepted it is unclear to what extent the same can be applied to the Forest of Dean (Hoyle *et al.* 2007). The imperial control of minerals seems to vary based on the value of the resource combined with local political and economic circumstance (Cleere and Crossley 1985, 66). Although there is evidence for a significant smelting sites at *Ariconium* and Monmouth from the late 1st century AD there does not appear to be any evidence for military control at either site (Hoyle *et al.* 2007, 112; Jackson 2012, 180). Growth during the 2nd century may represent an increased

civilian market due to the growth of settlements such as Gloucester, Cirencester and Caerwent nearby, or an increase in military demands leading to a lack of material available for civilian consumption (Jackson 2012, 179). The reduction in number of the sites which had been producing iron in the late iron age to early roman period has been given as evidence for military control taking over and shutting down small 'private ventures' to allow for concentration of resources (Walters 1992). But as the reliability of the dating and interpretation of these sites has already been called into question, then this interpretation should be treated with caution (Hoyle *et al.* 2007, 112). There appears to be no evidence for military control of the iron industry in the Forest of Dean during this early Roman period. It may have operated under imperial control through licensed private individuals, but there is no archaeological evidence to prove or disprove this. The local elites who had controlled the production of iron until the arrivals of the Romans may have continued the industry and resource along with the new Roman administration as is consistent with the assimilation of elites elsewhere in the empire (Hoyle *et al.* 2007, 113).

Walters (1992) divided the Roman Forest of Dean iron industry into neat parcels with expansion in the 1st and 2nd centuries, decline in the late 2nd – early 3rd centuries and a late 3rd century revival. Even without the direct military control of smelting in this area there is evidence for the expansion of the smelting activity. Sites such as Monmouth, *Ariconium* and Whitchurch became significant centres with development of new centres at Newent and Dymock (Hoyle *et al.* 2007, 113). The review of smelting at *Ariconium* (Jackson 2012) suggests that earlier estimations of scale of production at this site had been overestimated. That rather than being a full-time specialisation it may have been carried out only when the labour force was not otherwise engaged in, for example agriculture. Many of the late Iron Age/early Roman sites ceased to operate from the late 1st century AD. Little is known about these sites and the dating is imprecise but this cannot be used to support the view

that they were deliberately closed down as part of a military led centralisation of the industry (Walters 1992, 151).

There are numerous sites dating to the 2nd century AD which do not fit with the idea of a centralised iron industry. There are smelting sites associated with either established settlements or villas but also sites which are known from surface scatters whose association and status is not known (Hoyle *et al.* 2007, 114). These same categories are found in sites dating to the 3rd century AD, given this similarity it could be said the changes in the iron industry were limited to the large-scale sites on the periphery of the Forest of Dean.

It may be expected that the mixed economy of most rural villa sites would lead to at least smithing and in some cases smelting of iron to maintain and produce the iron required for domestic and agricultural practices (Branigan 1989, 42). Some sites, however, would have produced more iron than would have been required for the consumption of the estate. For example, The Chesters villa at Woolaston has been interpreted as 'a highly organising enterprise' with between 62 and 180 tonnes of iron being produced during the lifespan of the site (Fulford and Allen 1992, 205). The value of the iron smelting to the economy of the villa is difficult to speculate, but it seems likely that it would be a significant 'side-line', albeit not something upon which the whole villa economy could be based (Branigan 1989, 49).

The decline of large scale sites and the development of more dispersed smaller-scale sites may not be indicative of the exploitation of Forest of Dean ores, from either capitalising on the decline of the Wealden trade or the opening of the western seaboard, as suggest by Fulford and Allen (Hoyle *et al.* 2007, 117; Fulford and Allen 1992, 205). This downgrading and dispersion of sites may instead imply the end of military markets and growth in urban

development, with production incorporated into a local mixed economy, supplying local markets (Hoyle *et al.* 2007, 117).

Few of the sites in the Forest of Dean have been studied in detail using modern excavation and analytical methods. Even reports on known sites are ambiguous about scale, economic and social status, and perhaps most significantly, dating (Hoyle *et al.* 2007, 117).

To contribute to the existing corpus of information on the production of iron in Iron Age and Roman Britain the dataset used to inform this study needs to be rigorously examined. A suitable methodology for selecting and analysing the samples will be developed and applied to this study.

CHAPTER 3 DATASET AND METHODOLOGY

3.1 THE DATA

The data used for this project comes from several sources and even data for the same site may come from different sources. The archaeological context of a slag, on a site, regional and chronological scale is very important to be able to contextualise any analysis carried out on a sample of slag.

3.1.1 The Sources

The sources of data to be used are either published data such as monographs, published articles and online resources or unpublished data such as grey literature or new analyses for this project.

3.1.1.1 Published data

Monographs

There are two types of monograph used for this thesis, technical monographs and archaeological monographs. Technical monographs such as those produced by Historic England (formerly English Heritage) have a specialist focus rather than a particular archaeological site or hypothesis (Bayley 2001; Dungworth 2015). For this project the monographs produced by Historic England provide an overview of archaeometallurgy in Britain and introductions to more focussed areas such as 'Pre-industrial Ironworks' (Paynter 2011). Archaeological monographs are very important for this project as some of the sites which are being studied have only been published in monographs. Preston (2013) is the source material for three of the sites being studied in this thesis. It is the result of a small number of archaeological investigations by Thames Valley Archaeological Services in the period 2010-2012. The final archaeological monograph used for this thesis is Schrüfer-Kolb (2004), this work focussed on the transition in iron smelting from the Iron Age to the Roman period in the Northamptonshire Jurassic Ridge area. This monograph is

important as it covers one of the major iron smelting areas in Roman Britain. Both of these monographs include archaeometallurgical analysis carried out as part of the research.

Published Sites

Several of the sites for this site have been published as journal articles, these articles are from journals with either an archaeological or archaeological science focus. Archaeological journals present the results of archaeological investigations and are used primarily here for the archaeological background of sites as the metallurgical information can be limited (Catchpole 2007a; 2007b; Catchpole *et al.* 2007a; 2007b; Collard *et al.* 2006). Archaeological science journals such as *Historical Metallurgy* and *Archaeometry* are used for both archaeological and scientific information about sites and the slag recovered them (Crew 1998; Dungworth and Mepham 2012; Paynter 2006).

3.1.1.2 Online resources (including community groups)

It is becoming increasingly common in archaeology for the dissemination of information using online databases, for this project databases of archaeological sites are particularly useful. Websites such as the Archaeological Data Service (ADS 2017) give access to thousands of archaeological records from across Britain. The information from this can be used to create a GIS (Geographic Information Systems) plot of sites which can be used to compare and contrast sites. The Rural Settlement of Roman Britain project based at Reading University has a searchable database which although focussed on Roman settlements is possible to search for ironworking on the database (Rural Settlement of Roman Britain: an online resource 2016). The Wealden Iron Research Group have a history of almost 50 years of research into iron working sites in the Weald of Sussex and Kent, identifying hundreds of sites in this time. Each of these sites has been registered on their

online database (WIRGdata 2017). This database is searchable using a range of archaeological and archaeometallurgical parameters.

3.1.1.3 Grey literature analyses

Grey literature is the collective term used for reports which are produced for the planning process by developer-led archaeological projects. These reports are available through the individual companies either by request or through online gazetteers. Many of the developer-led sites which will be studied for this thesis are examples of this (Allen *et al.* 2013; Clay 2009; Brett 2004; Brett *et al.* 2004; Ellis 2013; Hoyle *et al.* 2007). These reports give the important archaeological context and description of the slag. These are important to understand the assemblages which have been deposited with a museum. Another example of grey literature reports which are useful for this project is the Geoarch archive (geoarch 2017) which is the work of Tim Young over the last 20 years. Many of his reports have been made freely available on the company's website. Geoarch is the largest archaeometallurgical consultancy in Britain and has produced hundreds of reports on metallurgical remains discovered on archaeological sites.

3.1.1.4 New analyses done for this thesis

A few of the sites being used for this project are not yet published or released as grey literature. All but one of these sites have been excavated since the start of the research into this thesis. The remaining site was excavated in the early 2000's but has not been published fully yet. This site, Hartshill Copse, is a gravel quarry near Thatcham in Berkshire which has been excavated in a series of phases. Earlier phases of this site are claimed to have produced the earliest evidence for iron working in Britain. The multiphase nature of this excavation means that later phases with less significant recoveries are being withheld for publication in a monograph.

The new sites excavated are from both developer led and community archaeology groups. In both cases the site has been excavated and the contextual information from the site has been made fully available in return for scientific input into site reports. As these sites have been recently excavated the full assemblage of what was recovered was made available for analysis and a full rigorous sampling strategy was able to be employed. These sites have been radiocarbon dated as part of the publication process so there is good quality dating available. This is not always possible in material from sites which have been excavated and fully published before being sampled from a museum assemblage.

3.2 SITES

The sites below have been selected for study as part of this thesis and will be defined into chronological periods, site types and production scale of the site. The geography of the sites will be discussed as an independent factor rather than a defining one. This is to avoid the continuing trend of a small sample of sites, or even individual sites, being used to define the entire iron production process of a period.

3.2.1 Iron Age sites

The Iron Age sites sampled can be split into three chronological groups, two main site types and three different scales. Chronologically the sites are divided into Early, Middle and Late Iron Age. The early Iron Age sites date from 800BC to 400BC and the middle Iron Age sites date from 400BC to 150BC. The late Iron Age period could be considered to have a 'hard' finish date of 43AD, however a transition period of interchange of ideas, people and cultures is more likely. Given uncertainties in the dating of many of the sites in this period, sites are likely to bridge these strict period definitions. Therefore, for the purposes of this project the Late Iron Age period will be considered as part of the transitional period. The two main sites types which have been identified are settlement related and isolated smelting sites. Isolated smelting sites are considered to be special locations where smelting was carried out distinct separate from a settlement. Settlement sites have evidence for both occupation and also for industrial processes. The three scales of site are single event, small scale and moderate to large scale. Single event sites have as the name suggests been used once for the production of iron, small scale sites were used more than once but potentially as one event and moderate to large scale sites were used repeatedly potentially over a long period of time and an increased volume of debris accumulated because of this.

Sadler's End, Sindlesham (SES)

An Iron Age smelting specific site discovered through evaluation trenching ahead of the construction of the new Wokingham Cricket Club ground (Taylor 2010). A detailed excavation of the iron smelting area was carried out, with the importance of the site being realised once Iron Age pottery was recovered during the early stages of excavation (Lewis *et al.* 2013, 3). The area of the site associated with iron smelting was limited to an area roughly 30m x 20m on a west facing downslope. The site consisted of a slag heap lying downslope and over a series of furnaces and possible furnaces. The slag mound was formed of two main depositional events, the upper level appears to have been disrupted by later agricultural activity. The furnaces range in size from small 0.3m diameter shaft furnaces to a single large furnace almost 1.4m in diameter (Lewis *et al.* 2013, 9). As well as the furnaces there was a number of small features associated with the smelting activity. There is a partial ring of stakeholes which are likely to represent some form of shelter or windbreak (Lewis *et al.* 2013, 33; Brown 1995, 119). The open area excavation also revealed a small number of features which were not associated with the iron smelting activity these predated or was contemporary with the smelting activity.

The site was dated using radiocarbon dates on charcoal recovered from features associated with the smelting activity. The earliest reliable date for a furnace (context 208) was 540-398 cal BC, furnace 33 was dated to 385-205 cal BC, both of these were smaller shaft type furnaces. The larger furnaces 221 and 505 were dated to 196-54 cal BC and 185-50 cal BC, archaeomagnetic dating of furnace 505 gave a date of 240BC ± 390 (Lewis *et al.* 2013, 30; Clelland 2013).

This site can be categorised as a specialist isolated smelting site.

Grazeley Road, Reading (GRR)

This site consists of a small unenclosed Iron Age settlement site consisting of a pair of roundhouses, one of which potentially had a small iron smelting furnace in the gully around its exterior. The furnace was initially uncovered in the side of an evaluation trench which led to the furnace being damaged and was not possible to fully excavate or examine this feature. The slag recovered from this site totalled only 12kg and is likely to represent a single smelting event. The slag was predominantly recovered from gully 2002 which was radiocarbon dated through charcoal from the fills of the gully to 760-503 cal BC. The spread of the slag through this gully suggests it was open when the slag was deposited (Ford *et al.* 2013).

This site can be categorised as an isolated smelting event on a settlement site.

Manor Farm, Finchampstead (MFF)

This site was uncovered during archaeological observation undertaken during groundworks for the construction of a series of agricultural structures. In the process of this work a single iron smelting furnace and a series of features containing iron smelting slag were also found. The possible furnace consisted of a depression filled with burnt clay measuring 1.2m across and 0.12m deep in a bowl shape. This site was dated to the 407-357 Cal BC by radiocarbon dating of a fragment of charcoal recovered from a pit containing smelting slag (Platt 2013).

This site would appear to be an isolated smelting event. However, the presence of a slag heap further to the north may suggest otherwise, we cannot be sure without further work.

Hartshill Copse, Thatcham (HCB)

This site was excavated in a number of stages in advance of gravel extraction. This site has potential evidence for iron working dating to the 10th century BC (Collard *et al.* 2006). Smelting slag was recovered from a number of contexts associated to the 5th and 6th centuries BC, this material was calculated to be at most 10% of a single smelting event (Youngs in Brett *et al.* 2004). During later phases of this site an in-situ furnace bottom was recovered, these phases are currently in the process of being written up. It would appear likely this furnace bottom would date to this period, based on the similarities in the archaeological contexts (Brett *et al.* 2004). This site has been suggested as the earliest evidence for ironworking in the British Isles (Collard *et al.* 2006) this is disputed due to the mobility of hammerscale, it is outside the scope of this thesis, focussed as it is on iron smelting, to discuss iron smithing evidence in sufficient detail to critique this.

This site can be categorised as a small settlement site with small scale smelting activity.

Matthew's Green, Wokingham (MGE)

An excavation on this site in advance of housing development revealed a small Middle Iron Age settlement with evidence of small scale smelting activity. A single ring gully associated with iron smelting slag was recovered and radiocarbon dated returning dates of 541-392 cal BC and 397-208 cal BC. There was no confirmed furnace remains on this site however, a single fragment of furnace slag is suggestive of the furnace size and shape indicating it was roughly circular and 200-300mm in diameter (Ford 2017).

This site is a small settlement site with small scale smelting activity.

Shooter's Hill, London (SHH)

Archaeological excavation during the filming of Channel Four's *Time Team* uncovered an Iron Age ditch which contained 63kg of slag. From the pottery assemblage recovered from this feature an early iron age date was suggested (8th century BC or later). Slag assemblage is mostly small pieces (<100g) and more or less complete. The feature containing the slag was dated through ceramics to Late Bronze Age to Early Iron Age (8th to 5th century BC) (Dungworth and Mepham 2012). As this excavation was limited the context of the iron smelting is not clear but it could very loosely be suggested to be a settlement site as it was recovered from a possible enclosure ditch.

Lightwater, Surrey (LW)

This site was excavated from 1985 to 1992 in summer excavation seasons by the Surrey Heath Archaeological and Heritage Trust (Heathland History 2013). A total of 4 tons of slag was recovered from the site, a single furnace was excavated which has suggested to be a non-slag tapping furnace. The site has been dated from ceramic evidence to be late Iron Age (Cole 1991).

The limited evidence from this site suggests that it is likely a large scale smelting site but it may also have been a moderate scale site operating over a long period.

All Canning's Cross, Devizes (ACC)

This site was excavated by the Cunnington's between 1911 and 1922, identifying an Early Iron Age settlement with associated iron smelting. The initial examination of the slag as part of this work must be one of the first scientific analyses of slag from an archaeological site. This attributed the slag to ore from the local greensand formations. This site was a settlement site with smelting evidence from the earliest Iron Age phases (Cunnington 1923). The importance of this site is discussed earlier for its position in Iron Age studies,

the slag sampled here has been ‘lost’ in Devizes museum stores until recently found in a cataloguing scheme carried out on the Cunnington’s archive. There is no contextual information available for anything of these samples, but this site is too important to be dismissed because of this.

Site	Period	Type	Scale
SES	MIA-LIA	Isolated	Large
GRR	MIA	Settlement	Single smelt
MFF	MIA	Isolated	Small
HCB	MIA-LIA	Settlement	Small
MGE	MIA	Settlement	Small/Single
SHH	EIA	Settlement(?)	Small
LW	LIA	Isolated (?)	Moderate/Large
ACC	EIA	Settlement	Small

Table 3, Summary of Iron Age Site Types

3.2.2 Transitional sites

These sites date from 150BC to 100AD covering the Late Iron Age and the period of contact and communication with the continent increased and the early period of Roman occupation. The late Iron Age especially in the south east of England is considered to be a period of increasing contact and communication with the continent. The influence of Belgic tribes on this area has been debated but there are undoubted cross channels in this period. The first few decades of Roman occupation have been suggested to represent the continuation of existing iron production methods and organisation (Cleere 1984, 96; Catchpole 2007b, 237). This transitional period is poorly understood and how much influence the preceding and forthcoming cultures had on each site may be very variable.

Rose Cottage and Dymock Sewage Works, Dymock

Dymock is located in North West Gloucestershire and it consists of a Roman roadside settlement which has been extensively studied since the mid 20th century. A series of small archaeological investigations have shown the extent of this settlement alongside the road which runs under this village (Catchpole *et al.* 2007b, 235). Dymock is a small scale rural settlement which has evidence of smelting from the earliest Roman occupation levels (Catchpole *et al.* 2007a, 146; Tavener, 2001). But despite this early Roman occupation there is no evidence yet found which suggests an Iron Age settlement preceding the roadside occupation (Catchpole *et al.* 2007b, 235). The settlement fits the pattern of roadside settlements across Britain (Finch Smith 1987). The evidence for iron smelting extends for at least 700m across the settlement. This settlement would appear to be a similar style settlement to Ariconium (Jackson 2012) but on a smaller scale, a mixed economy rural site whose wealth derives from metalworking (Catchpole 2007b, 237).

Rose Cottage, Dymock (RCD)

Rose Cottage was excavated in two phases of work firstly an evaluation which identified stone buildings, which were not fully excavated, as well as features containing slag and early Roman pottery, and a later limited excavation which did not include the stone structures earlier identified (Tavener 2001).

Dymock Sewage Works, Dymock (DSW)

The expansion of the Dymock Sewage works led to the excavation of an area of the enclosed settlement identified underneath modern Dymock. Slag was recovered from features dating to 120-150AD but there is nothing to suggest smelting continued beyond 150 AD (Catchpole 2007a, 217). As well as evidence for iron production evidence for non-ferrous metalworking in the form of a brooch mould fragment and matching brooch were found (Catchpole 2007a).

Stockbury, Kent (STO)

During archaeological monitoring of a pipeline near Stockbury in Kent Late Iron Age smelting works were discovered. The site consists of a number of sunken shaft furnaces associated with sunken floored buildings either above or adjacent to the furnaces. Potsherds were used to date this site to a hundred years of activity from c.50 BC to c.50 AD. The slag was analysed as part of the production of the excavation report and suggests a transitional type of smelting activity which is between non-slag tapping and slag tapping technologies. Given the location and date of the site is suggested that this evolutionary form is 'perhaps as a consequence of, or catalysed by, contacts with the continent' (Girbal in Allen *et al.* 2013). The preservation of this site is exceptional and allows for a good estimate of the furnace construction, paired shaft furnaces at least 1m in height (Allen *et al.* 2013).

Site	Period	Type	Scale
RCD	ERB	Specialised settlement	Moderate
DSW	ERB	Specialised settlement	Moderate
STO	LIA/ERB	Isolated	Moderate

Table 4, Summary of Transitional Site Types

3.2.3 Roman sites

These sites fall into two chronological groups, five main site types and four different scales. Chronologically the sites are divided into early and middle to late. The early roman sites date from the 2nd century AD they are potentially closely associated with the transitional sites. The middle to late Roman sites date from the 3rd and 4th centuries AD they reflect the established iron industry once the Roman influence has stabilised. The main site types are specialised rural, specialised urban, central production sites, satellite sites and settlement related sites. Specialised rural sites are sites whose sole function is the production of iron, in a rural setting, specialised urban sites fulfil the same role in an urban context. Central production site and satellite sites are related with a central site being the core of a network of satellite smelting sites. Settlement related smelting sites are essentially the same as the Iron Age sites of the same type, smelting evidence from settlement sites, however there are two variants of this, smelting in settlements and smelting at isolated farmhouses or villas. The scale of the sites is divided into small, medium, large and very large. Small scale sites are considered to be single or small scale multiple smelting events, medium scale sites were used on multiple occasions but not enough to leave an impact on the landscape, large scale sites reflect a site on an industrial scale which had an impact on the landscape and very large sites are the equivalent in production scale as a *manufactorium* and still have a visible presence on the modern landscape.

Worcester City Football Club, Worcester (WFC)

Evaluation of this site revealed a series of linear features containing a large quantity of iron slag, therefore the site was designated for a full excavation ahead of groundworks associated with construction work. During this excavation a large quantity of iron smelting slag (470kg) was recovered from contexts dating to the Roman period. There was no evidence on site for a furnace however given the quantity of slag and the preservation of fragments of furnace lining it would appear likely a furnace was located close to the site. The dating of the Roman period of this site was broadly given as Roman with most being early (1st to 2nd century)(Bray 2016).

Beauport Park, Battle, Hastings (BP)

This site has been held up as being a key example of the scale and organisation of the Roman iron smelting industry in the Weald. An extremely large 'bank' of slag was observed by the local rector was observed in 1859 and seems to have then been quarried for road surfacing material in the local area. A local antiquarian observed the removal of this slag, noting the presence of pottery fragments (Rock 1879). Rock's accounts refer to the finding of several Roman coins, Samian ware and other pottery (Brodribb *et al.* 1988). The site was subject to a small scale archaeological investigation in 1924 when a gully was examined and the layers described in detail, however no discussion of the wider site was made. In the 1960's exploration of the heavily overgrown site was made to examine the 'Romano-British ironworkings' noted on the Ordnance Survey maps. During this process, through the use of divining rods the location of a bathhouse was identified. Plans for a golf course on this site were changed to accommodate this site and excavations on the site of the bathhouse were carried out from 1970 to 1971. The bathhouse was excavated fully and shown to have been covered by a 'landslide' of slag and then covered and preserved by the

excavators and local enthusiasts. A television led investigation was carried out in 1999 through which geophysical survey showed the possible layout of the whole industrial site. This site has been estimated to be the third largest iron production site in the Roman Empire. A small sample of material was obtained from the Battle and District Historical Society who had collected it from the surface of the site.

Reddings Lane, Staunton (RDL)

During a small scale evaluation an assemblage of iron smelting slag was excavated from features which were dated through pottery from the 1st century AD to the 2nd century AD and from the 3rd century AD. This site was not known to have existing archaeology but is possibly adjacent to a Roman road and within 300m of a possible signal station. Geophysical survey on the site showed a number of ditches forming two enclosures containing further features, a number of discrete high magnetic responses. The pottery dating to the 1st Cent AD would potentially date some of the iron smelting activity to amongst the earliest in the Forest of Dean (Ellis 2013).

Federal Mogul, Lydney (FML)

An evaluation of 33 trenches in advance of a development of agricultural land. The potential of the site was identified as there was evidence from the land to the north and north east of medieval settlement. Archaeological investigations to examine these found evidence for Roman structures and iron smelting. The features which had slag recovered from them were dated by pottery to the 2nd to 4th centuries AD. The features across the site were quite shallow with the suggestion being made that much of the site had been truncated by later agricultural practices (Brett 2004).

There were few other features recovered from this site so it would seem likely this was an isolated smelting site but this could not be confirmed without further excavation.

Sherracombe Ford, Devon (SHF)

Sherracombe Ford was examined as part of a project to understand the historic iron industry of Exmoor. Two working platforms and corresponding heaps of smelting waste were identified through survey, there were also a number of smaller isolated platforms. From the excavation of one of these platforms three phases of smelting activity were identified from the late 1st century AD to the mid 3rd century AD. As well as the smelting furnaces and deposits of smelting slag there was a thick layer of hammerscale and slag fragments forming a smithing working floor. Hammerscale and magnetic susceptibility study of the site located a likely location for the location of an anvil (Bray 2006).

This site is a specialist iron production and iron working site.

Bradenham Bloomery, Bradenham (BRAD)

A single furnace was excavated on this site. The furnace shaft was well preserved in the side of a pit excavated into the side of the hill. The shaft was D-shaped at the base with the flat side facing into the pit. The shaft was angled back into the edge of the pit and is round at the surface. The base of the shaft had an in-situ mass of slag. The adjacent pit contains the debris from the smelt, this includes fragments of furnace lining suggesting this furnace was used on more than one occasion. This site has been dated to an early Roman date from the ceramic evidence. This site is a small isolated smelting site, however it was a very targeted excavation and there may be other features nearby (Green *Pers Comm*).

Clearwell Quarry Extension, Lydney (CQS)

The slag from this site was found from the same ditch context, during an evaluation for the extension of Clearwell Quarry. This quarry had earlier evidence for Saxon iron smelting in the form of a series of slag pit furnaces (Pine *et al.* 2010). This context also contained a number of fragments of 2nd century AD pottery amongst the slag. This deposit suggests a

2nd century furnace was operating in the immediate vicinity of this feature. As smelting evidence was only recovered in a single trench it would appear that the smelting activity on this site was at a small scale (McNichol-Norbury 2016).

Site	Period	Type	Scale
WFC	Early to Mid RB	Specialised settlement	Moderate/Large
BP	Mid RB	Isolated specialised	V.Large
RDL	Mid RB	Isolated specialised	Small/Moderate
FML	Mid to Late RB	Isolated specialised	Small/Moderate
SHF	Mid to Late RB	Isolated specialised	Moderate
BRAD	Early RB	Isolated specialised	Small
CQS	Mid RB	Isolated specialised	Small

Table 5, Summary of Roman Site Types

3.3 BIASES

Industrial sites and their debris have been understudied when compared to settlement, ritual or burial sites. However, when the site and artefacts are treated correctly then they have the potential to answer wider questions than simply technical. The history of ferrous slag analysis has been dominated by technical analyses, first being conducted by metallurgists. These studies examined how the process of iron smelting was carried out; but they often stopped short of linking this to the wider archaeological picture (Morton and Wingrove, 1969; 1972). Archaeometallurgists "have rarely ventured any opinion on the social context of early metallurgy, preferring to stick closely to technical interpretation" (Killick 2001, 486). This situation has been made worse by the highly technical reports and articles packed with data tables and sample micrographs which are not easily accessible (Daoust 2015).

Archaeometallurgical studies are often affected by the samples available (Daoust 2015). Slag recovered from archaeological contexts has changing levels of quality depending on its taphonomic history. Most material is recovered from either excavations or surface collection. Even material which has been collected using the same method can be treated differently post-recovery, leading to different qualities of data. The point of discussion is how much slag is required to be able to understand a site. Some forms of slag are more indicative of the processes forming the smelt and unfortunately these are often small, infrequent and potentially easily missed. Yet the opposite can also be an issue during some excavations unusual or 'eye catching' may be preferentially selected whilst the remainder of the assemblage comprising the mundane majority is ignored (Bayley *et al.* 2008).

The most desirable assemblage - the archaeometallurgist's 'holy grail'- is one which they are able to excavate, process, describe, report and analyse themselves. This is rarely

possible and the risk of concentrating on a single site is isolating the results from the wider picture. It is also impractical to recover an entire slag mound, considering many weigh in the hundreds if not thousands of kilograms of material. A sample must be recovered and inherent bias is already put in place by this, any further subsampling increases the level of bias. Whilst this bias can be considered and reduced by an informed selection of the sample it still remains.

The scarcity of archaeometallurgists, especially those working in iron and iron smelting, means that it is rare for the focus of a research excavation to be iron smelting (Juleff 2009, 559; McDonnell pers comm; Archmetals 2011; Bayley, *et al.* 2008, 26). There are however a few local archaeological groups who are passionately discovering and excavating iron smelting sites (Bayley *et al.* 2008, 26-27). Of these the Wealden Iron Research Group is the largest and most active group, producing its own journal focussing on their work as well as maintaining an online database of the iron production and working sites found within this region (WIRGdata 2017). Despite this the greatest contributor to the number of excavated iron smelting sites from Britain is commercial archaeology. This is especially true of the excavation of sites from outside the areas which have been conventionally identified as iron production areas (Preston 2013). Often the constraints on these projects lead to strategies being decided upon quickly at site assessment and evaluation stages (Bayley *et al.* 2008, 26). This requires site staff to be able to identify this material at least to a pyrotechnological process so that further expert input to excavation strategies can be obtained.

The increased use of scientific dating on industrial sites has also increased the number of sites dated to the Iron Age particularly. There are limitations on the accuracy of the dating, there is a plateau in the C-14 calibration curve which corresponds with much of the Iron Age (Garrow *et al.* 2009, 99). When a furnace structure is excavated then it can be possible

to use archaeomagnetic dating to date the last firing. There is a lack of data from this period which would allow for the construction of a detailed calibration curve. The increased number of dates is a marked improvement but it raises potential issues with sites dated by pottery typologies, or slag typology. It is very difficult to date slag based on the macromorphology, the same forms of slag are repeated through time. Sites have been identified to either the Iron Age or Saxon periods or to either the Roman or Medieval periods.

There are essentially two forms of deposit in which metalworking debris is found. Primary deposits, where metalworking took place and secondary deposits where the slag was redeposited. With smelting slag this would be material recovered from within furnaces or tapped slag within a tapping pit. Secondary deposits range from slag heaps created to clear the smelting area to the inclusion of slag in middens, pits and ditches close to the smelting site (McDonnell and Starley 2002, 1). It can also be removed from the vicinity of the smelt to be used as hardcore, for surfacing or as part of the charge in blast furnaces (Bayley *et al.* 2001, 11-12). Each of these deposits alters the bias which is associated with the material recovered from it. When slag is recovered from a primary context there is no doubt that the material is related to the context it was found in. Some forms of slag are more likely to have been recovered from a primary context, for example slag blocks from a slag pit furnace.

Slag is often commented upon and analysed as part of the production of post excavation assessments, (Lewis *et al.* 2013; Young 1997; 1999; 2003; 2004a; 2004b; 2005; 2007; 2008; 2010; 2012a; 2012b; 2013; 2014a; 2014b; 2015; Young and Kearns 2010; 2011). The content of these reports can vary dramatically from total weight to detailed context by context analysis. One trend is the location of specialist slag and industrial debris reports in the appendices with brief summaries hidden amongst the other ‘inconsequential’ artefacts

reports. It is very common for iron smelting sites to be treated as individual isolated units. Rarely are they compared to other sites, when they are the comparisons are often restricted by the nature of the reporting. This is not to say that sites are universally poorly reported and disseminated (Halkon and Starley 2011; Young Young 1997; 1999; 2003; 2004a; 2004b; 2005; 2007; 2008; 2010; 2012a; 2012b; 2013; 2014a; 2014b; 2015; Young and Kearns 2010; 2011; Dungworth 2007) but the investment of time and resources is never the same as a more public friendly, attractive site.

The curation of slag in museums has been hampered by two main issues, the heavy, bulky nature of the material and its lack of aesthetic appeal. These mean that it takes up a lot of the finite space in storerooms of museums and is not seen as suitable for display. Since the increase in developer archaeology through the 1980's, 1990's and into the 2000's museums have been struggling for space and one of the artefacts considered surplus to requirements is slag. With museums charging for the deposition of artefacts commercial units are unwilling to deposit slag. These factors mean that this material can often be disposed of without being fully studied. In the ideal world then a proportion of metal artefacts and waste should be analysed from every assemblage, bringing this data together could help reveal patterns and trends (Bayley *et al.* 2008, 15).

The identification (or misidentification) of slag has led to the nature of the ironworking process being misunderstood for many sites. The mere presence of slag on sites has been assumed by some to be indicative of smelting. But when examined in detail this interpretation can be changed. The difference between smelting and smithing, when found in isolation, is a crucial economic difference between producer and consumer. The lack of definition between smithing and smelting slag has the further impact that the full number of and distribution of smelting sites excavated is not fully known.

There is a major stumbling block in the standard and consistency of analysing slag (Killick 2015a, 244). There is no single established terminology to describe the types of slag or its morphology. There have been a series of terminologies created but often the variation of slag within a study leads to extra terms being added. There are several types of slag which are agreed upon, these form the large proportion of assemblages. These have an understood place in the production process, however some types are not fully understood. When the slag is not understood, it is difficult to suggest the most suitable method for further analysis.

Optical microscopy is limited by a similar lack of standardisation (Killick 2015a, 244). There is a known small number of mineral phases which occur in certain forms in the slag (Bachmann 1982, 14-18), but there is no set of reference images or material which can be used as a comparison (Killick 2015a, 244). Often the recognition of the microstructure of slag is only learnt through being directly taught, restricting the accessibility of published data to those who have learnt this skill. In other fields where microscopy is heavily used such as geology then there are atlases of reference materials (Killick 2015a, 244). This can only be rectified by a wide scale programme collating existing studies with new optical analyses of archaeological and experimental slags. The production of slags from experimental smelts where the details of the process have been identified could allow comparisons and better understanding of the microstructure.

A variety of different methods have been used for chemical analysis of slag. The three main methods used have been X-Ray Florescence (XRF) (Schrüfer-Kolb 2004; Veldhuijzen 2003), Scanning Electron Microscopy (with Energy Dispersive Spectrometry (SEM-EDS)) (Paynter 2006) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Charlton 2015). Each of these different techniques have their own strengths and weaknesses (Table 6).

	Strengths	Weaknesses
XRF	Non-Destructive, minimal sample preparation, relative ease of basic use, can detect down to parts per million (PPM), rapid analysis	'Surface' technique only, size of analysis – beam diameter and depth of up to 1mm, struggles with lighter elements (non vacuum chamber systems), cannot detect sodium (a common minor element in the glass phase) background noise often limits detection levels to 0.1%,
SEM-EDS	Targeted analysis, coupled with imaging, consistent detection levels of major and minor elements	Destructive and extensive sample preparation, struggles with lighter elements, cannot detect trace elements, detection levels limited to 0.1%
ICP-MS	High detection levels over a wide range of elements, accurate measurement of trace elements	Destructive analysis, sample has to be homogenised (unless using LA-ICP-MS), requires comparable chemical standards, bulk analysis rather than more targeted

Table 6, Chemical Analytical Methods Strengths and Weaknesses

The nature of a material should be a crucial factor in the choice of method(s) used to analyse it. Slag is a heterogeneous material so bulk chemical analysis must be undertaken with care. It is one of the few archaeological artefacts which can be destructively analysed as a routine. These factors favour the destructive techniques. When used correctly ICP-MS has the potential to give very useful data especially where a suitable research question has been formed. This is especially true with laser ablation (LA-ICP-MS) where areas can be targeted using a laser to sample a known feature of the sample (Blakelock *et al.* 2009). The bulk analysis of slag is preferred for provenance methods and looking at the contributions of the different raw materials to the final composition of the slag. The ease of use of XRF and portable XRF in particular could be suggested to be a negative factor to the results produced from this method. Analysis can be made without expert understanding of the science behind the analytical method or the subject of analysis. SEM-EDS has drawbacks

in terms of its accuracy and the level to which it can be called fully quantitative. The lighter elements of the periodic table are more difficult to get accurate analyses for than the heavier elements. It has the major advantage however of being able to target particular areas or phases for analysis. This gives a level of extra flexibility to answer hypotheses brought about by the heterogeneous nature of slag. Bulk chemical analysis is the more applicable method for analysing the inputs to the smelting process. Targeted analysis of the different phases is more suited to examining the formation of the slag and how the slag solidified. Therefore, my study will be using SEM-EDS as the main analytical method, using this it is possible to also to take bulk area analyses.

The main issue with the chemical analysis of slag is that there is no set reference collection for the microstructures and different phases (Killick 2015, 244). There has been a reference slag used to calibrate bulk analysis (Kresten and Hjärthner-Holdar 2001). The slag was crushed and homogenised and analysed by several laboratories and methods. However, the issue with this reference is that it has been created from archaeological material and therefore there is a limited amount of this available (Kresten and Hjärthner-Holdar 2001, 48). As this material has been crushed it is not possible to use it as a comparative standard for the different mineral phases. This has been the only standard created for the study of slags from bloomery smelting.

The biases in my samples are predominantly concerned with the quality of the excavation and what material has been deposited with a museum. There are two sources of slag, commercial units and amateur groups. The material from commercial units is then further split into material which was obtained directly from a unit or from a museum after being deposited. Collecting the material directly from an archaeological company can reduce the amount of bias as the excavated material can be examined as part of the sampling process. The material which has been sampled from museums is not necessarily a representative

sample of the sites assemblage. The site reports of the deposited material allow for the bias to be understood, showing what material was excavated and deposited. Although some amateur societies work with the same level of skill and detailed recording as professionals this is not always the case. The quality of the recovery and dissemination of results by amateur societies can be limiting. Sites can be left unpublished and unreported for a significant period. then they may be published only in a local journal and not spread to the wider archaeological community. Some amateur archaeological groups such as the Wealden Iron Research Group have an established record of excavating and reporting on iron smelting sites. Some of my samples have been recovered from sites with known furnaces present but others have been recovered from sites without identified furnaces or from surface collection. All the material has been identified as smelting slag using macromorphological analysis.

The methods I have chosen means that there will be biases introduced to the samples. The selection of samples has the potential to cause biases as outlined above. However, by using macromorphological analysis of the slag before I prepare or analyse any sample the intention is to reduce this risk by understanding the assemblage prior to any destructive sampling. This is partially resolved by taking all samples as far as optical analysis before choosing the samples for chemical analysis. This again has the possibility for bias being introduced with odd or 'interesting' microstructures being favoured. The microstructures can be studied in terms of the chemical composition and the furnace conditions. Using SEM-EDS as an analytical method allows for the examination of both the bulk chemistry, individual phase chemistry and the form of the different phases. Where possible several samples from the same site are used to both illustrate variation and compare similarity. Within each sample a number of areas will be analysed using as large an area as possible.

3.4 METHODOLOGY

3.4.1 Sample selection

Slag is very common on smelting sites; therefore, a sampling strategy is essential. Selecting the right sample is important to be able to be able to understand the smelting process.

The two main types of assemblage used for this work are excavation and museum assemblages. The volume of slag from a smelting site alongside the limited storage capacity of many museums have resulted in sub-samples being retained.

3.4.1.1 Excavation assemblages

Sampling from an excavation assemblage allows for a more direct selection of slag. It can be based on the full range of archaeometallurgical residues including those pieces which would not be deposited with the museum. These assemblages can be sampled representatively, allowing the specialist to summarise and sample accordingly. In theory, this representative sampling can give a more complete picture. Given this freedom a specialist can oversample or overemphasise one aspect of the assemblage. The bulky and heavy nature of slag makes selective sampling on location more favourable than taking too much material. Taking too much of one particular portion of the assemblage must be carefully avoided.

The process of summarising needs be repeatable at different locations and with different assemblages. The process involves a series of stages to understand what material is in the assemblage and how it comes together to represent the entire smelting process. The character of the assemblage needs to be determined and understood. The best way to do this is simply handling the material and working through the slag. By sorting through the material like this, it is possible to build a picture of what is present, and its potential. Where a fully comprehensive report of the site and the slag has been completed, then this can be

used to speed up the process what may be suitable for sampling. Where such a report has not been completed, then sample selection should be done in cooperation with the excavators to complete the archaeological picture. The character of the assemblage is shown by the types of slag present and the proportions of these different types. Having this understanding of the assemblage gives crucial information to how the smelting activity was operated and how the site would have functioned.

A basic macromorphological understanding of the slag is required to be able to make the decisions on what to sample. This can be based on existing typologies such as McDonnell (1986) and Crew (1995), but using the addition of experience of the material. The details of macromorphological analysis are covered elsewhere but the method of slag separation and the variety of assemblage are the important factors to be considered here. The sampling must consider the majority and minority types of slag represented within the assemblage. It must also consider the importance of the different types of slag to the smelting process. Once the character of an assemblage is understood then sub sampling of the assemblage can be carried out. To be able to conduct a detailed macromorphological analysis of the slag, fragments as complete as possible are preferable. Where a fragment of slag is too large for practical handling or transport, then sub-sampling is carried out; in this situation, a detailed description of the sampled material must be produced. Where practical, photographs of the slag before being sub-sampled are also preferable.

Being able to sample from a whole assemblage is the preferred method for collecting samples, this allows the specialist to reduce the unknown bias to only that which was introduced in excavation. Access to this form of assemblage is less common than a museum or curated assemblage. The specialist would be able to access this type of assemblage only when they have an existing relationship with the excavators.

3.4.1.2 Museum assemblages

The British museum system is becoming overwhelmed with the volume of finds which are being produced from developer led archaeological investigations. Because of this some museums are limiting the type and quantity of artefacts accessioned. One of the artefacts which is often restricted is smelting slag. The volume of slag produced from a smelting site is generally very substantial, especially compared with other artefact types such as ceramics or bone. Therefore, the assemblage of slag which is deposited with a museum is rarely a representative assemblage. It is not always clear what material has been deposited with the museum. The deposited material must be examined and selected based on what material is present and information from any specialist or site report available. The selection criteria used on the excavation assemblage forms the basis of the selection from museum assemblages. The material selected for deposition in the museum has introduced biases in a more complicated way than the excavation assemblages. The selection of material for deposition in museums is rarely carried out by the specialist. Therefore, the material available in the museum may not be fully representative of the site. In sampling from a museum collection, one should take this into account. To counter this bias, one should aim to take samples from as wide a number of contexts as well as a wide variety of types of slag as available.

3.4.2 Sample preparation

The first stage of preparation is to make sure the slag is clean to show any surface detail. The slag is washed and any surface dirt is removed using a stiff plastic brush. For more stubborn and dried earth the slag may need to be soaked in water before the earth is loosened enough to be able to be removed by brushing. The slag is left to dry thoroughly, after which it is examined visually.

Once the macromorphological analysis of the slag has been carried out, the results are used to decide where to sample from. For microscopic analysis, a subsample with a surface area up to 2cm x 3cm is needed. The slag can either be cut, to target a particular aspect of the sample, or fractured if a more general sample is suitable. For cutting slag, diamond edged water cooled circular saws in the Oxford University Centre for the Environment (OUCE) Geolab were used. Using the saws available, it was possible to cut samples down to a centimetric size. In a larger mass of slag, where there may be significant heterogeneity through the mass, a series of sequential samples was needed. A large cutting wheel was used to roughly cut samples before using a smaller saw to cut them to size. For fracturing masses of slag, a hammer is used. For both processes, cutting and hammering, appropriate health and safety considerations were acknowledged and thus, eye protection and safety gloves were worn. In addition to this, while cutting samples, it was necessary to have an appropriate facemask with disposable air filters to prevent inhalation of dust particles and water particles with suspended dust.

The pieces of slag were shaped by hand using silicon carbide grinding paper to flatten the sample so that is would sit flatly in the mould. An appropriate sized mould for the sample was chosen and lined with release agent before the placing the sample inside. Each sample was given a unique code, printed and placed alongside the sample in the mould. The resin used was Buehler Epokwik, a cold-setting clear resin which can be cured with heat if necessary. Once the resin had been poured over the sample it was placed in a vacuum chamber to ensure resin penetration into as many of the voids in the sample as possible.

Once the resin sets firm the excess is removed using a rotary grinding machine and silicon carbide grinding paper. The sample is ground using increasingly fine grades of grinding paper, alternating the direction of grinding to remove the scratches from previous papers. Once the sample has been progressively ground smoother to the final grade of paper it is

thoroughly cleaned to remove any fragments of grit before it is polished. The samples are polished using rotary polishing wheels initially with 6µm diamond suspension then 1µ diamond suspension using distilled water as a lubricant. The residue of the polishing liquid is washed from the sample between each polishing stage. The samples are then thoroughly cleaned once again to remove all surface contamination. At this stage the sample is fully prepared for optical analysis.

For the analysis of the sample by scanning electron microscopy (SEM) there are a small number of further steps required. The sample is placed in a vacuum pre-pump chamber to draw out any trapped water. Many of the samples are by nature porous and water can become trapped within them which can remain even when the sample appears dry. While in the SEM the sample is held in a vacuum, if there is moisture trapped in the sample it will be difficult to get sufficient vacuum or the vacuum will be degraded when the moisture gets drawn out. Therefore, the sample has to be placed in a vacuum to ensure this does not happen at a later stage. To ensure a clear picture and stable analysis using SEM then the sample must be able to be conductive. As slag is not conductive by its nature it must be coated, a thin coat of carbon is vaporised onto the surface of the sample. This requires drawing a vacuum over the sample and passing current through a carbon filament or rod causing it to vaporise, rather than burn, and coating the sample in a thin layer of carbon. The sample is placed within a metallic holder and connected using carbon putty or tabs and a copper strip to complete the connection to the holder.

3.4.3 Multiple analyses approach

A holistic approach to analysing archaeological materials is standard operating procedure in ceramic analysis. However, it has not become standard in archaeometallurgy, this can be partially blamed on the limitations of destructive analysis of metal objects. Macroscopic analysis of slag gives important information and opens further questions which can be

answered using microscopic and compositional analysis. Using these methods as combined analyses there are less loose ends left. It is also not simply that the total result is greater than the sum of its parts, the combination of methods removes some of the negatives of each method.

3.4.3.1 Macroscopic analysis

The external form of the slag is important in understanding the role the slag played in the smelting process. The formation of the slag gives key indicators to the type of smelting process being employed. The method of slag extraction or retention is the defining characteristic between basic furnace types. There have been many attempts to characterise slag by its external appearance (McDonnell 1983; 1986). The form of the slag reflects the point during a smelt at which the slag cooled below its solidus temperature and therefore the point at which it becomes isolated from any ongoing process. The slag is visually examined before and after it has been cleaned, where possible. Some formations of slag are loosely bound together and if vigorously cleaned can break apart. Once cleaned key features which link the slag to a point in the process are studied. As well as these markers which describe the slag type other details can be identified. The presence and type of any surface damage shows if an assemblage is close to its origin or has been moved. Material recovered from an extant mound or features excavated from a smelting site are likely to be from a context close to the original source. Concretion on the surface of the slag can be the effect of groundwater, and can be a potential indicator of chemical weathering which can affect further analysis. These properties are subjective as they are based on the personal experience and knowledge of the specialist. A systematic method of examining the macromorphology of slag can be achieved by applying numerical values to different aspects of the slags appearance (G. Juleff *pers comm*). This results in a string of numbers

which can be used to quantify the slag recovered from a site. This method requires access to a whole assemblage, something which is difficult to achieve.

It is not the intention of this thesis to rewrite all slag typologies; indeed, the limited chronological and geographical scope of this project and its restriction to smelting makes this impractical. Therefore, a simple descriptive method developed from studying iron smelting remains predominantly from across southern Britain will be used. It is based around describing the role of the slag in the smelt, starting with whether the slag was retained within the furnace or removed from it. Certain characteristic surface morphologies of the slag distinguish between slag removed from or retained within the furnace. Using these it is possible to begin classifying the slag to the broad types agreed upon by existing typologies (Table 7). There are other forms of slag which are not directly relevant to the smelting of iron, such as smithing and fuel ash slag, which can be found in association with smelting but will not be analysed as part of this study. As well as the slag, the technical ceramics from the furnace are an important part of the assemblage. The furnace lining can help to reconstruct the furnace when it is damaged or not present. Features such as the tapping arch and the number and locations of tuyeres can be found from the furnace lining if found. One thing which can only be determined from the furnace lining, whether in-situ or as part of the waste assemblage, is whether a furnace was relined and how many times is was before being replaced. Tuyeres also form an important part of the understanding of the smelting process when found as part of an assemblage. The vitrification or slagging of a tuyere can show how far it reached into the furnace, the level of vitrification can be a rough guide to the temperature and duration of the smelt. There is even the possibility that the tuyeres could be completely consumed during the smelt if the temperature was high enough and the slag level reached the tuyere. Unfortunately, inasmuch as furnace lining

and tuyeres are not consistently found on smelting sites and rarely become curated in a museum assemblage, it is unlikely that there will be material from enough sites to make a worthwhile comparison.

Type/Name	Surface feature	Removed/Retained	Size
Furnace Slag	Irregular, no obvious surfaces	Retained	Variable
Furnace bottom	Shape of furnace base, upper surface irregular/smooth	Retained	Large
Slag Block	Shape of pit used to collect slag	Retained	Large to very Large
Flow Slag	Ropey flow/smooth all surfaces,	Retained	Medium to Small
Tap Slag	Ropey flow/smooth upper surface, lower surface has impressions of ground surface	Removed	Medium to Small
Raked Slag	Distorted upper surface, drag marks upper and lower surface	Removed	Small
Prills	Smooth surface, droplets	Retained/Removed	Small to very Small
'Smelting Slag'	Fractured surface – identification limited	Retained/removed	Small to Medium

Table 7, Macromorphological Typology

3.4.3.2 Optical microscopic analysis

Optical microscopy of slags is limited by a lack of standardisation (Killick 2015, 244). There are a small number of known mineral phases which occur in certain forms in the slag (Bachmann 1982, 14-18), but there is no set of reference images or material which can be used as a comparison (Killick 2015, 244). Often the recognition of the microstructure of slag is only learnt through direct transmission from a skilled practitioner to an 'apprentice'. This restricts the accessibility of published data to those who have learnt

the skill. In other fields where microscopy is heavily used, such as the geosciences then there are atlases of reference materials (Killick 2015, 244). The absence of such an atlas for archaeologists can only be rectified by a wide scale programme looking at existing studies and collating the results of them with new optical analyses of archaeological and experimental slags. The study of slags from experimental smelts where the details of the process have been identified could allow comparisons and better understanding of the microstructure.

Reflective light microscopy or metallurgical microscopy uses the principle of differing reflective index to determine the mineralogical composition of the sample. The sample has to be polished to a mirror finish to allow for the light to be reflected. Iron slag, both from the smelting and smithing processes, is formed of number of mineral phases within a glassy matrix. The different phases have different reflective indices and also different forms. These phases have the same composition as naturally occurring minerals and those names are used (Bachmann 1982, 14-18). The proportions and form of the different phases in the slag can only be affected by the inputs and the operational conditions of the furnace. The phases that are present are a result of the composition of the inputs and the form they take is largely related to how the furnace was operated.

Most iron smelting slags have three main components or phases; fayalite, wüstite and glass, the form and relative amounts of these reveal the smelting process.

The most commonly found silicate is the iron silicate mineral fayalite (Fe_2SiO_4). This is found as elongated laths or blocky massive crystals. The difference between these is related to the cooling conditions. if the slag has cooled quickly then laths will be formed (plate 1)[3]. If the slag has been allowed to cool more slowly, blocky crystals will form (plate 2).

[3] Unless otherwise noted example micrographs are not samples studied for this thesis.

Fast cooling can be brought about by interaction with solid material which is a lot cooler than the liquid slag and also the air outside of the furnace. Both forms will be larger and more developed if they have had a longer period to cool. With blocky massive crystals generally meaning that the slag was retained in the furnace the size of the crystal reflects the cooling time of the slag. However, as laths are thought to have formed quickly the difference in size of these is likely to be linked to the distance between the liquidus and solidus temperature of the slag. A small gap would lead to smaller crystals being formed while a larger gap would allow larger crystals to develop.

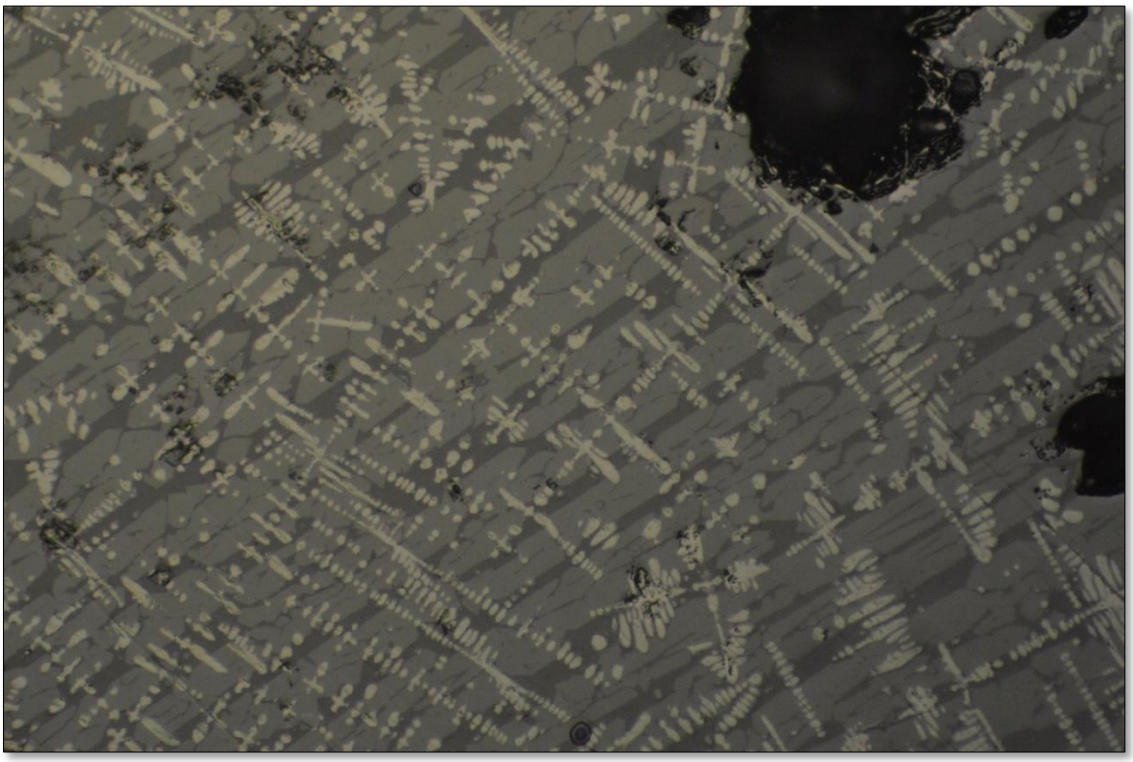

Plate 1, Example of elongated fayalite laths, with skeletal wüstite

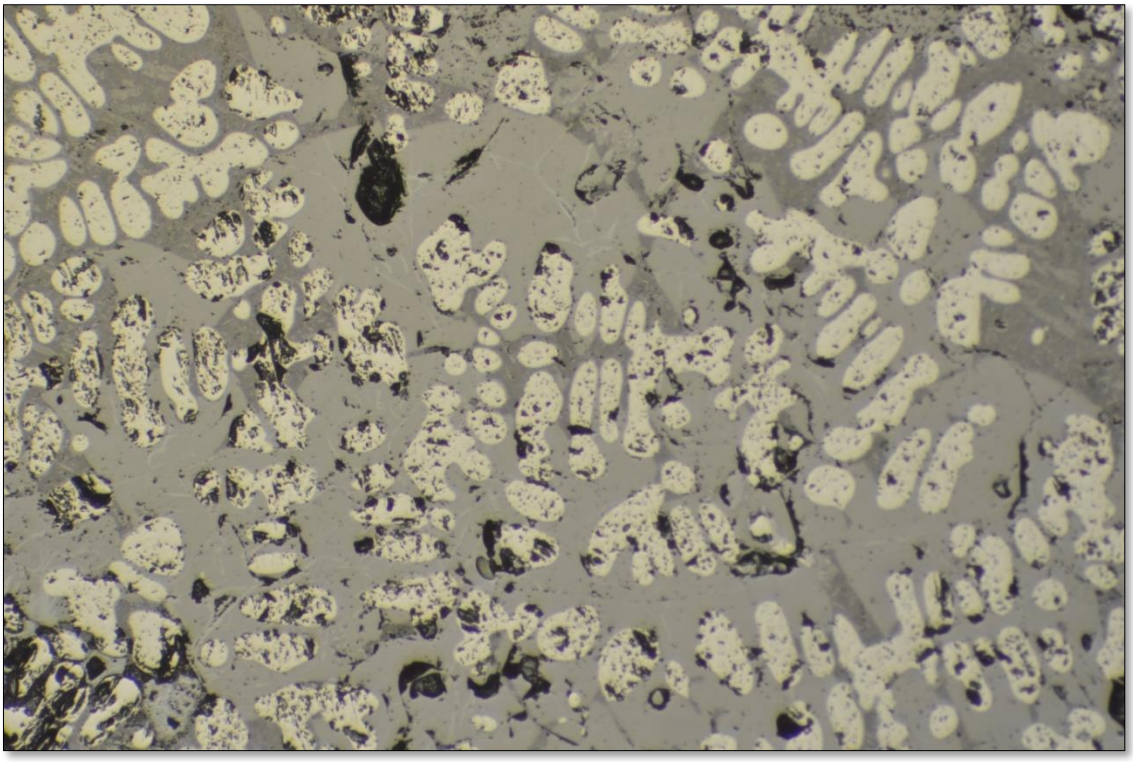

Plate 2, Examples of blocky fayalite crystals, with globular wüstite dendrite

Iron oxide is usually present in the form of either wüstite (FeO) with magnetite (Fe_2O_3) occasionally found. Wüstite is found in either globular or dendritic form, the level of development of the dendrite is an indication of the amount of time the crystal structure had to develop. Dendrites are tree like structures which grow from a central spine to have branching arms, this spine is the primary form with the branches from this being the secondary development and the 'leaves' on the branches being the tertiary stage. This can be found in either globular (plate 2) or skeletal form (plate 1), it is not clear what this difference represents but it is possibly linked to the temperature of the smelt. Magnetite when present indicates an oxidising environment, when present it is found on the surface or freeze lines of slag which has been fully liquid. It is either found in a globular form or more commonly a blocky cubic form. The amount of iron oxide present can be used as an indication of the reducing conditions of the furnace. If there was a highly reducing

atmosphere present in the furnace, then this would be shown with a lower percentage of iron oxide present as it would have been reduced to metallic iron.

The glass phase consists of the portion of the slag which has not been incorporated into a mineral phase (plate 3). As the mineral phases have formed into crystalline structures as the slag cools the liquid portion of the slag becomes enriched in the elements which do not form these phases. The enrichment of these elements results in a mixture which is below its crystallisation temperature and a glass is formed in these non-equilibrium conditions. Occasionally visible within the glassy phase are fine crystalline structures these are formed when the slag has cooled rapidly enough that the liquid slag still contains the combination of elements required for the formation of crystals and these are rapidly formed in a fine matrix within the glass. The glassy phase can represent the differences between different raw materials as the crystalline structures will form according to their fixed compositions.

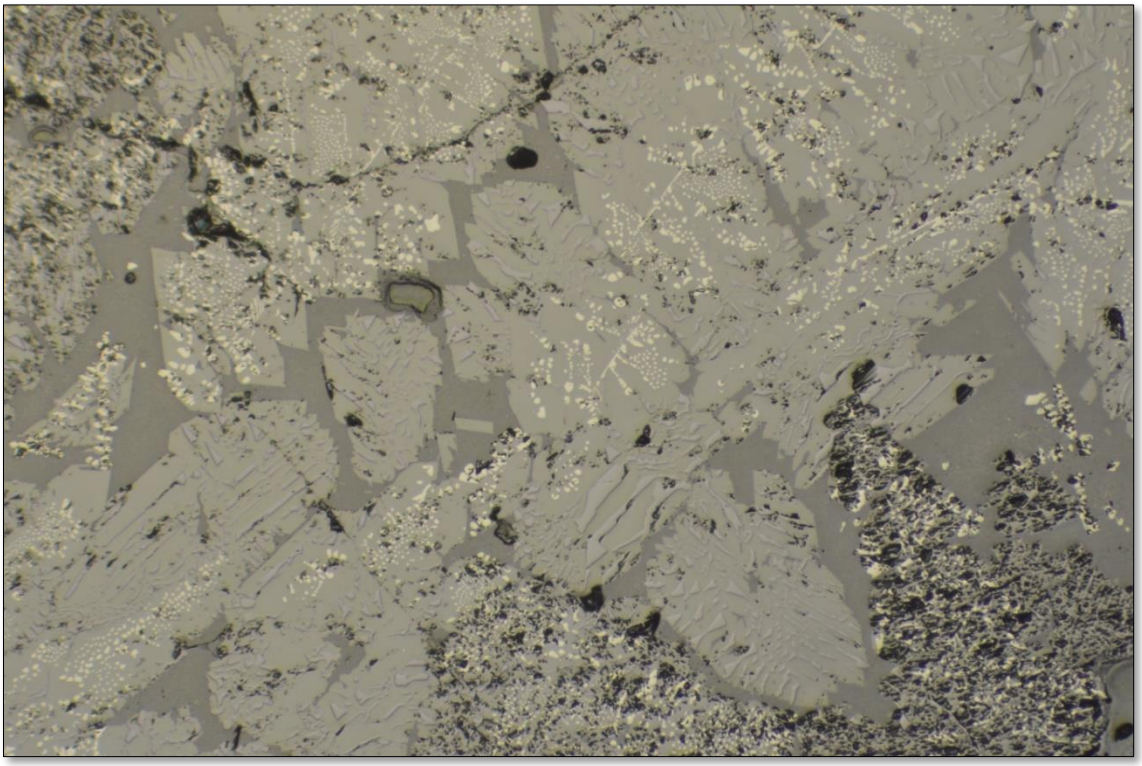

Plate 3, example of glass rich (dark grey areas) slag

Metallic prills are a fairly common feature of bloomery smelting slags but not present in every example unlike the phases above. As the slag may have been separate from the bloom for much of the smelt then metal trapped within the slag may have been exposed to different reduction or oxidisation conditions. Therefore, it is not directly possible to compare the trapped metal to the final product of the smelt. The form of these prills can show how close to the point of reduction the slag was at the time it solidified. Two main forms are often found globular or droplet prills (plate 4) and coral iron (plate 5). Coral iron consists of thin strings of metallic iron within the slag which have not yet coalesced together into a larger piece of iron. If these prills are large enough then it should be possible to etch these to reveal their microstructure.

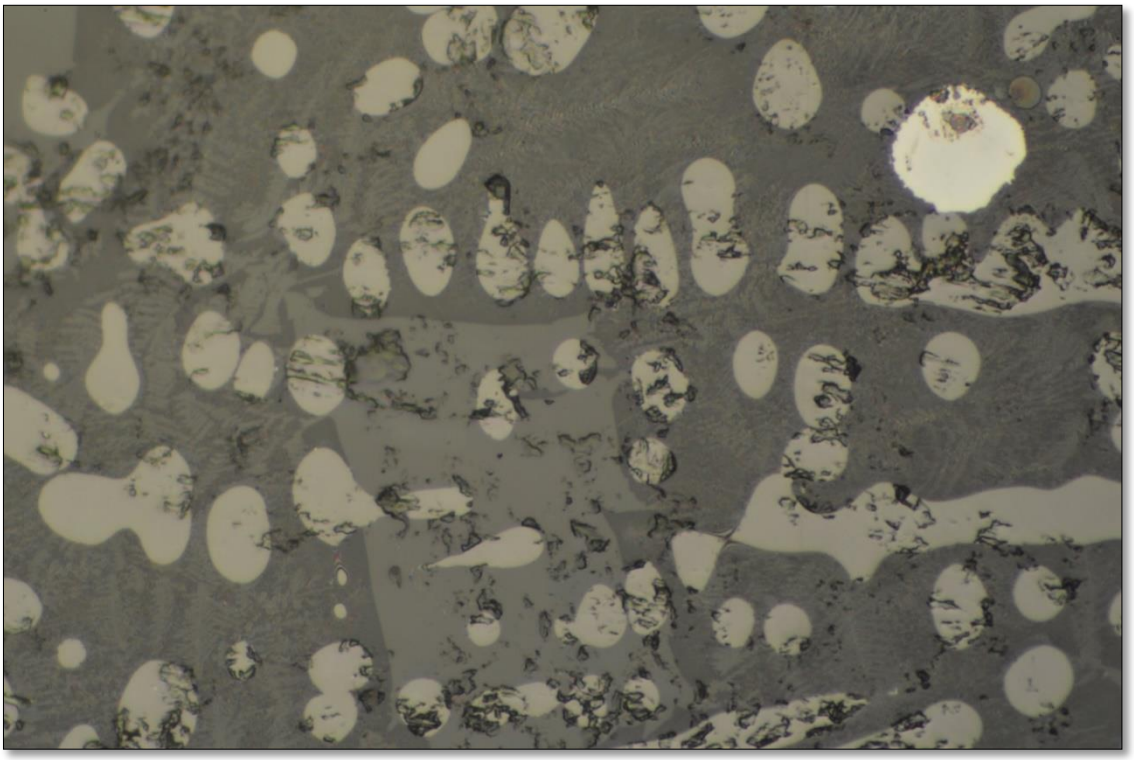

Plate 4, Example of a globular metallic prill

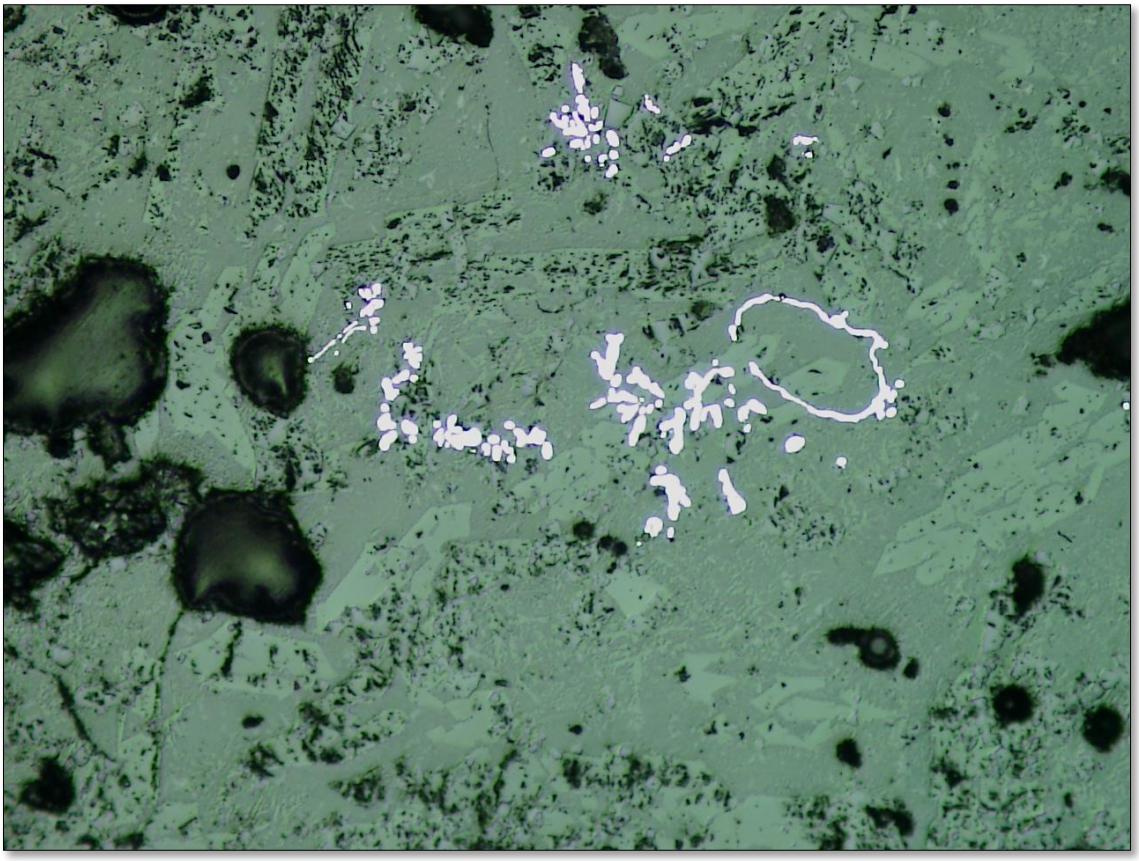

Plate 5, example of coral iron prills

Hercynite is an aluminium iron oxide mineral, one of the spinel group. It is present in slags resulting from smelts with a high alumina content, either from high alumina ores or inputs from technical ceramics. It appears in a blocky form which appears to be raised above the flat polished surface, a result of relief polishing caused by a difference in the hardness of different phases (Plate 6). Unlike many of the other phases hercynite is only present in one form, as blocky crystals, the size of which can correspond to the rate at which it cooled.

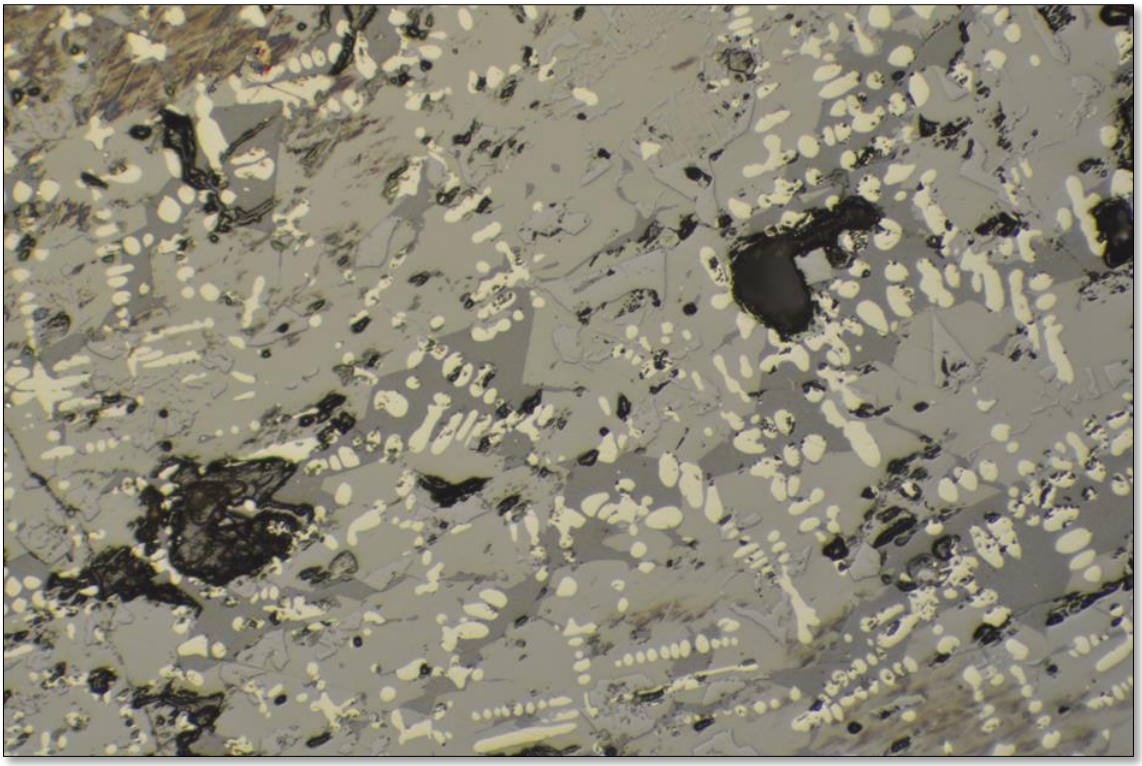

Plate 6, Example of fine hercynite crystals

Each of these different phases is identifiable not only by shape and form but also by the comparative colours. Because the sample is viewed as a block with reflective light the true colour is not shown, with a greyscale reflection visible. The more reflective materials like the iron and iron oxide have a lighter colour, while the phases which reflect less like the silicate and the glassy phase are much darker. Metallic iron is the most reflective being bright and shiny unlike the white and matt iron oxide. Silicate is a light grey colour with the glassy phase being the darkest.

As previously mentioned, studies are hampered by the lack of a standard reference collection of the microstructures of slag (Killick 2015, 244). This is a factor which may deter new researchers from taking up this aspect of studying this material. Learning how to study and analyse slag microstructures has been limited to studying published reports and information passed by word of mouth. Without a standardised reference collection of this material, we remain in some doubt about the accuracy of reports (Killick 2015, 244).

3.4.3.3 'Life History'

The combination of the macromorphology and micromorphology for each site reveals the 'life history' of the iron smelting operation. The macromorphology of a broad assemblage shows how the furnace was being operated. The individual details of the smelt can be shown by individual features of the macromorphology but how these would have affected the smelt can be shown by the micromorphology.

Although individual pieces of slag can be diagnostic for details of the smelting operation the non-diagnostic pieces of slag can also reveal some of the 'life history' of the smelt.

3.4.3.4 Electron microscope analysis

Scanning electron microscopy has an important function in the analysis of archaeological slag, especially from iron smelting. The method allows for the analysis of the microstructure and chemical composition of the slag. This type of microscopy uses an electron beam instead of light and the different ways in which this electron beam reacts to the sample result in different information. The electron beam is created by a tungsten element which are then controlled using a system of magnetic lenses which focus the beam and allow it to scan over the subject. The scanning of the beam across the sample in a series of sequential lines allows for an image to be build up from the responses to the electron beam. This beam then interacts with the sample resulting in a series of different emissions being given off. Electron Microscopy has 7 different modes of operation which are commonly used; backscattered electrons, cathodoluminescence, auger electrons, transmitted electrons, specimen current secondary electrons and characteristic X-Rays (Postek *et al.* 1980, 47). Of these the two which are most useful for this research are back scattered electrons and X-Ray emissions. Of these two the back scattered electrons are discussed here as they are used for imagery rather than chemical analysis.

Backscattered electrons are those which have been subject to single or multiple scattering events (Postek *et al.* 1980, 54). The electrons are scattered by elastic collisions with the nucleus or outer electrons of a sample atom (Postek *et al.* 1980, 50). The back scattered electrons have an energy which is roughly comparable to the atomic weight of the atoms of the sample. The electrons are given off in a number of directions based on the nature and number of the collisions within the atom. As they have a high energy level (50 eV or more) they travel in a straight line and do not require a charged receiver to attract them. This detector is located around the electron column and therefore directly above the sample but as the electrons are scattered the strength of the signal captured by the sensor is lower. This is especially useful for the study of iron smelting slag as it allows a clear separation between phases based on chemical composition. One downside to back scattered electrons is that they create a larger area of excitation than secondary electrons giving response from below the surface as well as the surface. The level of energy is shown by the brightness of the image broadcast onto a computer screen. A higher atomic number atom will be shown as being brighter than a lower atomic number atom. When applied to iron smelting slag this means the phases with more iron present will be brighter, with metallic iron being brightest and iron oxide being next brightest. Fayalite as an iron silicate will be a mid-tone grey due to its combination of low atomic weight silica with iron. The glass phase will be a darker tone again with its lack of iron and composition of generally low atomic weight elements. The tone of the rarer elements is similarly related to the chemical composition.

The scanning electron microscope in the Research Laboratory for Archaeology and the History of Art is a JEOL JSM - 5910 connected to a desktop computer running Oxford Instruments INCA program (JEOL Ltd 2001; Oxford instruments 2006). This allows for image capture connected to an analytical software. The quality of the image has the same

controlling factors as with a cathode ray tube screen, the number of individual measurements and the spacing between them changes the quality of image.

3.4.3.5 Chemical analysis

The chemical analysis of the slag is carried out using scanning electron microscope – energy dispersive spectrometry or SEM-EDS. This uses characteristic X-rays given off by electrons displaced from the outer electron rings which have characteristic energy levels depending on the number of electrons and number of electron rings. The X-rays are segregated by their energy levels and captured by a semi-conductor which then translates this x-ray energy into an electrical signal which is amplified and transferred to the linked computer running the INCA software package.

The combination of chemical analysis with imagery means that analyses can be targeted to a particular phase or area. The heterogeneous nature of direct iron smelting slag means that there can be significant variation which if not acknowledged could lead to incorrect interpretation. To study the bulk chemistry a series of 5 area analyses will be carried out. These will all be taken with the microscope at the same magnification of x100 and with the analysis parameters maintained across all samples. The INCA analysis software can be set to take analyses across a range of processing times, these are independent of the number of x-rays being received. This setting is kept consistent between analyses and samples to limit the number of variables (Oxford Instruments, 2006). The number of x-rays being emitted (and therefore able to be captured in the receiver) is related to the nature of the material, the size and strength of the electron beam and the distance to the sensor. It is possible to maintain the same strength of electron beam (20KeV) and the when the sample is located correctly it is a consistent distance from the sensor. By altering the variable of the beam size, known as the spot size, it is possible to control for different materials (Oxford Instruments, 2006). The INCA software has built in systems to allow the

measurement of the received x-rays so the spot size can be varied to fine tune the x-rays received.

This data will be used to compare across the different samples and used to determine possible ore sources, through the raw chemical data, the minimum temperature of the smelt, through the liquidus temperature of the slag, the reduction conditions in the furnace, calculated through the relationship between iron oxide and silicate in fayalite and the viscosity of the slag over the operating temperatures of the furnace, using modern slag viscosity calculators.

The bulk chemical composition is determined by the mean of the normalised analysis from at least five bulk area analyses. This will then be compared to the summary of existing European bloomery slag composition compiled by Pleiner (2000, 252) (table 8).

MgO	Al_2O_3	SiO_2	P_2O_5	CaO	MnO	FeO
0.5-3%	<1% low, 1-6% elevated, >6% high	15-40%, >34% high	<0.75% low, >1.5% high	2% low, 2-5% slightly elevated, 5-10% significantly elevated, >10% high	<1% low, >3.5% high	40-70%, >50% high

Table 8, Typical European bloomery slag composition (from Pleiner 2000, 252)

The raw material contribution to the slag composition will be established using the method of Charlton *et al.* (2010, 355) (table 9).

	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Ore	X	X	X	X		X	X	X	X
Clay		X	X		X		X		
Fuel Ash	X			X	X	X			

Table 9, (adapted from Charlton et al. 2010, 355)

By plotting a normalised composition onto a FeO – SiO_2 – Al_2O_3 ternary diagram it is possible to estimate the liquidus temperature of the slag, and therefore the minimum temperature of the hottest part of the furnace. These will be calculated using the methods used by Rehren *et al.* (2007). Most analyses of bloomery slag fall within the fayalitic region of the diagram, drawn out between two areas of lower melting temperatures (Rehren *et al.* 2007, 212, Fig. 1 – Fig. 9 below).

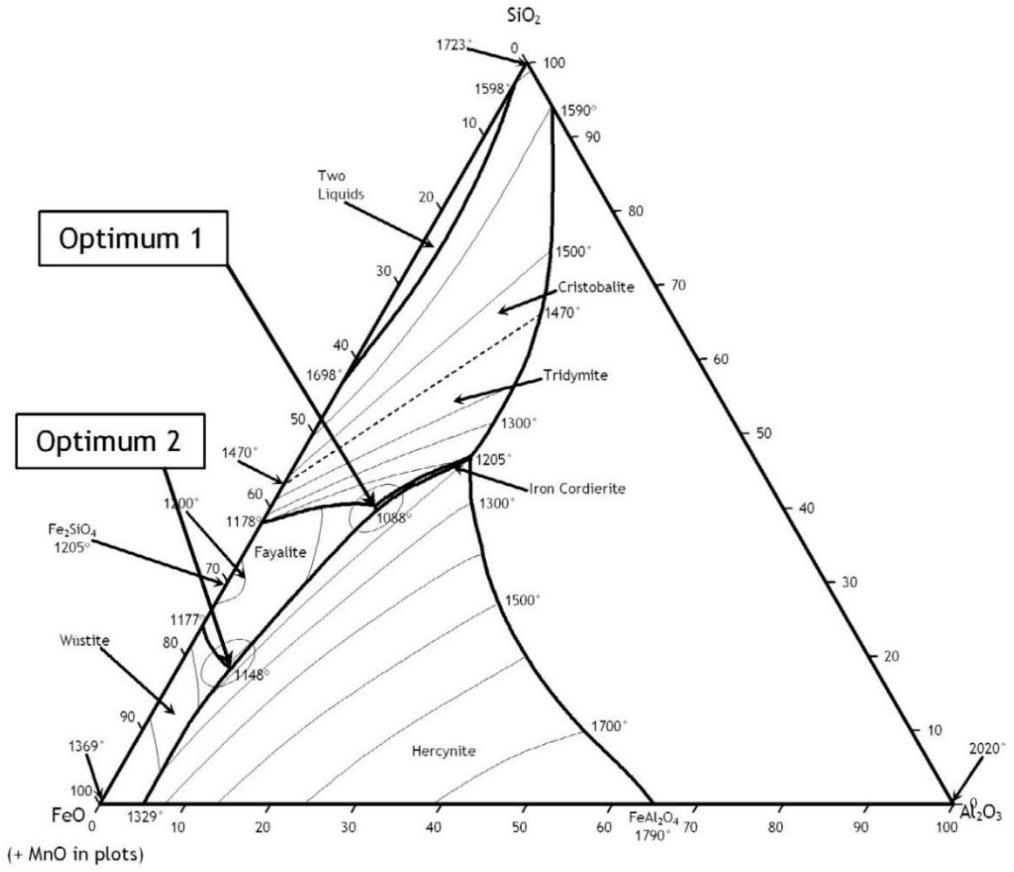

Figure 9, FeO-SiO_2-Al_2O_3 phase diagram (Rehren et al. 2007, 212)

The reduction conditions in the furnace are broadly estimated by using Charlton's Reducible Iron Index (RII) (Charlton et al. 2010, 356, referred to as S-value in Charlton 2007, 211). A value of 1.0 would be the equivalent of a pure fayalite slag, a slag where an

ideal amount of iron was used to flux the silica in the formation of slag. A value of over 1.0 indicates a composition that would have excess silica, or a more reducing condition in the furnace. A value below 1.0 would be increasingly rich in unreduced wüstite, the result of a less reducing condition (Charlton 2007, 211). The accuracy of the calculation relies on the assumption of a common ore source and estimate of the clay contributions from the furnace wall (Charlton et al. 2010, 356). Therefore, to directly compare the raw numbers from each site would lead to an inaccurate conclusion, to counter this the quantitative measurements from each site will be transferred into an informed qualitative estimation of the reduction conditions. The calculated values will also be presented to demonstrate the variation present at each site. The reduction conditions are important to how the smelting process would have been carried out as it determines the amount of metal reduced from the ore and the amount of carbon available to absorb into the iron.

While this is an oversimplification of the variation that can occur, it is useful to create a qualitative visualisation of the reducing conditions. Because of this it will be used for a coarse ‘less reducing’ vs ‘more reducing’ definition for each sample and the trend for each site.

The viscosity of the slag is a result of the chemical composition as well as the operating temperatures of the furnace. The composition determines the behaviour of the slag but by increasing the temperature the slag can become more liquid (figure 12).

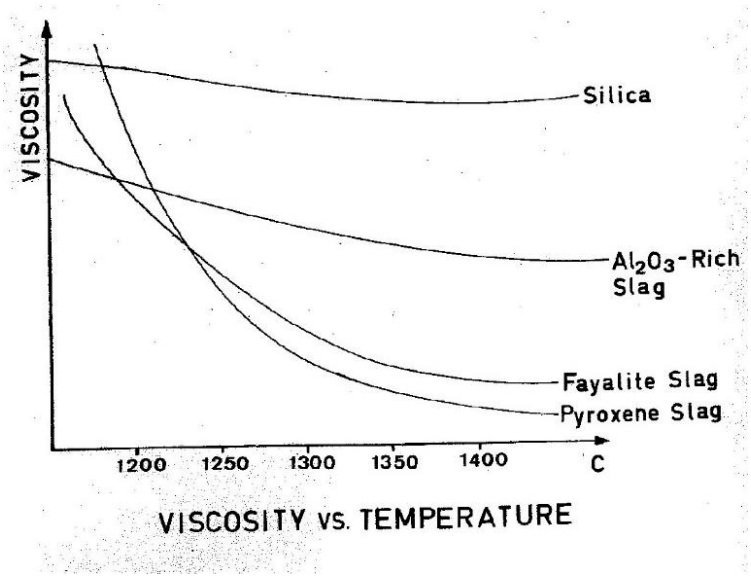

Figure 10, Viscosity vs temperature of slag (from Bachmann 1980, 131)

The viscosity of the slag close to the liquidus temperature is controlled by the liquidus temperature (Kresten, 1986, 44). The different major oxides in the slag can increase or decrease the viscosity of the slag (figure 13). Several different models have been employed to calculate the viscosity of the slag. These have often been repurposed from other fields, generally geochemistry and modern metallurgy, because of this they are often do not cover the composition of bloomery smelting slag. Geochemical models do not cover the elemental composition of slag therefore a modern metallurgical calculator will be used here to compare within this assemblage (Algoness 2017) The calculator uses the composition to calculate the viscosity in Poise at a variable temperature. The viscosities will be calculated from 1150°C upwards in 50°C steps to cover the temperature range which bloomery smelting furnaces have been predicted to have operated over.

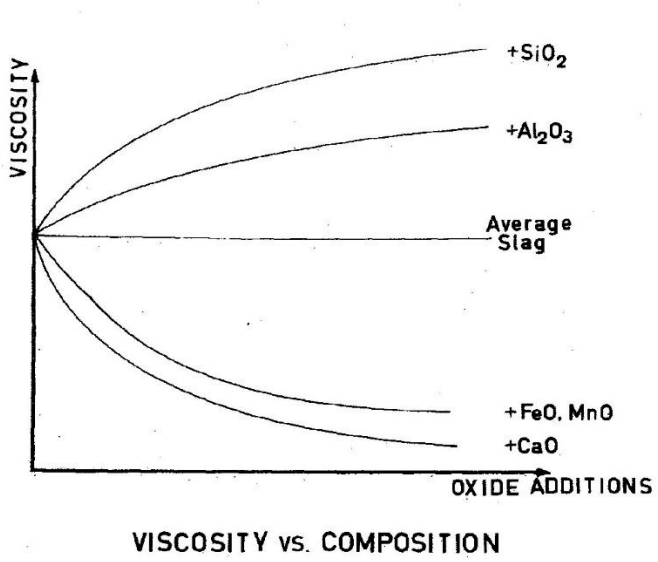

Figure 11, Viscosity vs composition of slag (from Bachmann 1980, 131)

The Poise of the slag samples will be compared to tables of modern, everyday materials (vp-scientific 2010), a viscosity of 15 will be considered to be a free flowing slag.

The following chapter consists of the result of the application of these methods as a combined suite of analyses on the samples selected. The selection of samples took into account the biases inherent and introduced by the selection and analysis and will be considered alongside the results through the remaining chapters.

CHAPTER 4 – RESULTS

4.1 IRON AGE SITES

4.1.1 Sadler's End, Sindlesham (SES)

Macromorphology

This site is an isolated specialist smelting site consisting of a spread of slag 20m by 30m covering 4 confirmed furnaces, up to 8 possible furnaces and a smithing area. The smelting activity on this site has been dated from 540-398 cal BC at the earliest to 185-50 cal BC.

The site has been estimated to have produced around 1700kg of iron, the equivalent of 2200 currency bars (typical weight 800g) (Lewis *et al.* 2013, 23; Crew 1995).

The assemblage of material from this site is dominated by slag which was retained within the furnace. Despite this overall assessment of the material there are very different forms of slag produced from this site. This can be explained by the reuse of this site over a period of time with different forms of furnace operating on the same site. The slag from this site can be roughly split into larger and smaller fragments. The larger fragments formed from more or less liquid slag coalescing within the furnace as the smelt progressed. As they are an accumulation of the slag during the smelt they could in theory record changes that happened during the smelt (Humphris *et al.* 2009). This could be studied by taking sequential samples to create a section through the mass (plate 7).

Plate 7, Cross section of unstratified furnace bottom

Smaller fragments of slag were recovered which appear to have been formed by slag descending through charcoal to create small runs or prills of slag. These prills would have been fully liquid but would have descended from the hottest area of the furnace and would have solidified before forming a larger mass. This assemblage was extensively studied during the post excavation work associated with this site (Lewis *et al.* 2013). Several masses of slag have impressions of plant material on the lower surfaces. Both straw and

wood impressions suggest that the furnace charge may have been supported away from the base of the furnace for the start of the smelt.

Plate 8, straw impression in the base of sample SES 32 95

The larger masses of slag, recovered from contexts 263, 221 and the ‘large mass’ and unstratified samples all contain fragments of unconsumed charcoal in the lower portions of the mass indicating that the early part of the smelt did not consume all of the charcoal of the charge. The inclusion of charcoal but not ore into the base of the slag mass suggests that the furnace was heated with a charcoal only charge creating the temperature and redox conditions to produce slag soon after the ore was charged into the furnace.

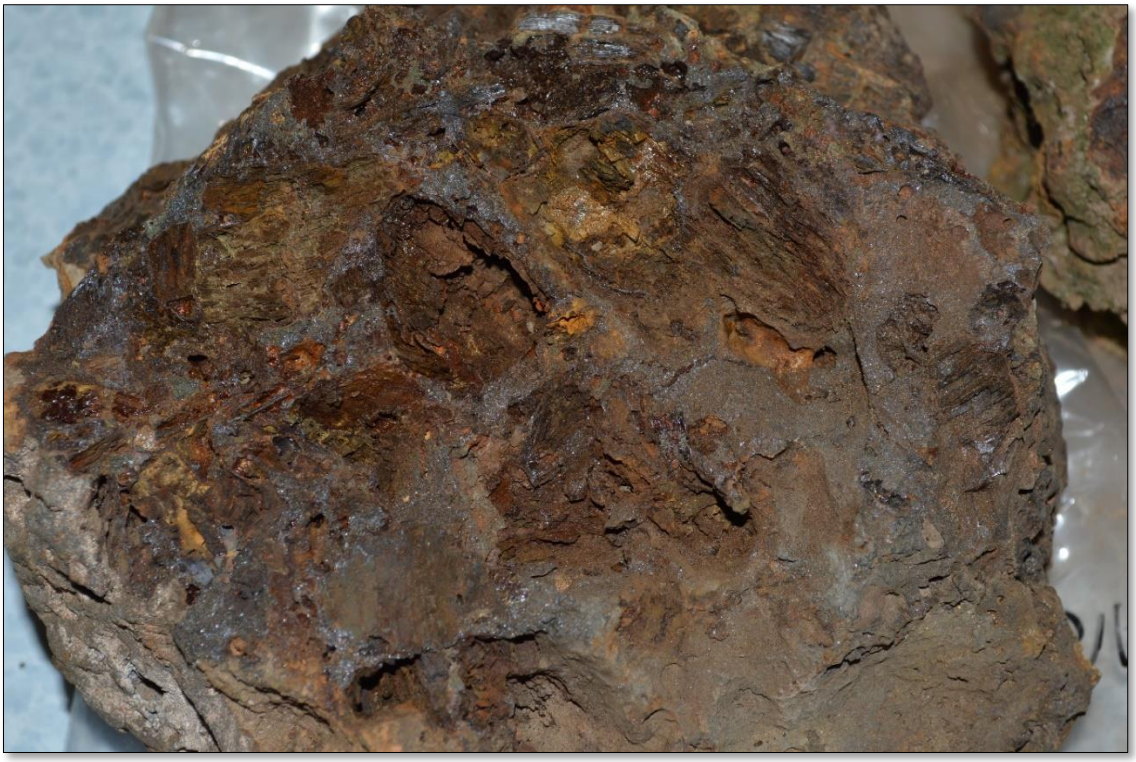

Plate 9, trapped charcoal within ' large mass' sub sample

Micromorphology

A series of sequential samples were taken from across the ‘large mass’ of slag produced in the large furnace and from the mass of slag from furnace 221 and the unstratified mass which matches the same form.

These sequential samples show that the smelt progressed in a similar fashion despite being from different furnaces and different smelts using the same furnaces. The three sequentially sampled masses which could have only been produced in furnace 505, based on the size of the slag mass and the furnace structures excavated, have similar microstructures but there are subtle differences between them which indicate that the smelts that produced them had different reduction and temperature conditions. These masses all have the same main phases present in their microstructures, fayalite, wüstite, interstitial glass, hercynite and metallic prills. The form of the fayalite changes in a consistent fashion from lath or blocky lath form in the lower portions to a larger more

blocky form in the centre and upper regions of the masses. This would suggest the lower portions, those first formed and furthest from the high temperature zone of the furnace, cooled over a shorter thermal gradient than the higher parts of the mass. This indicates that the first slag formed descended through the furnace to the base and once there was able to cool initially quickly then more slowly allowing for the growth of laths leading into more blocky fayalite.

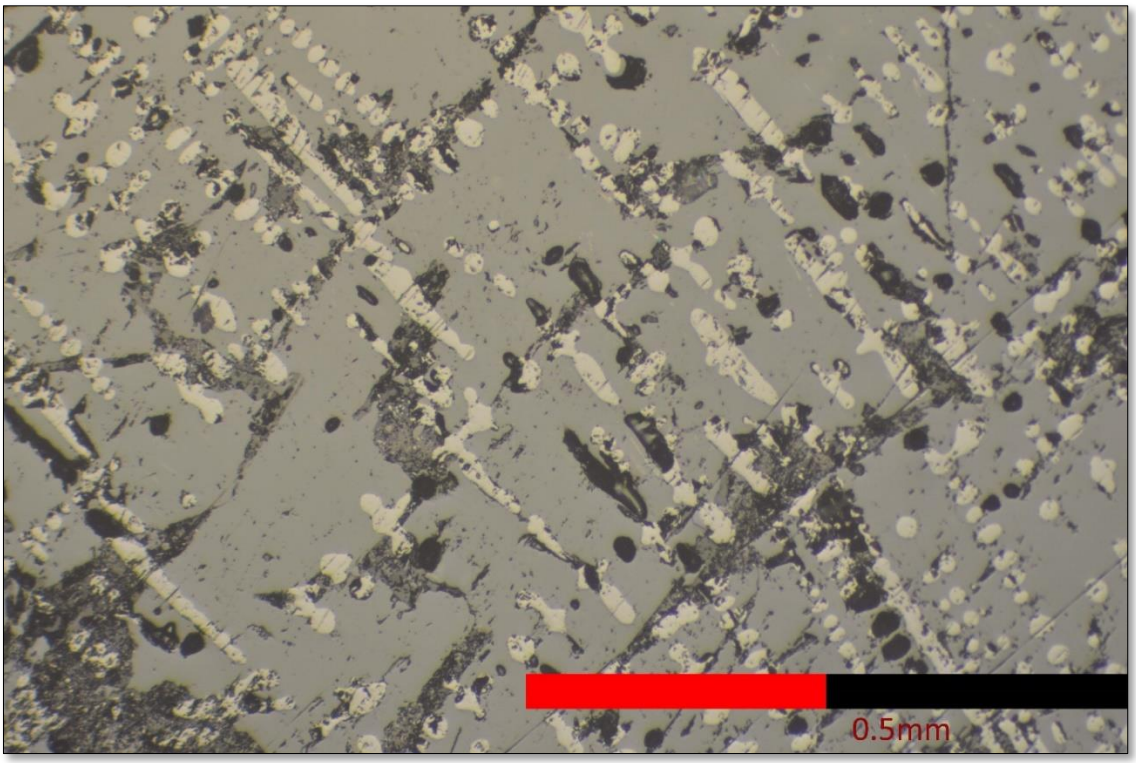

Plate 10, SES 263 375 3 - showing blocky fayalite

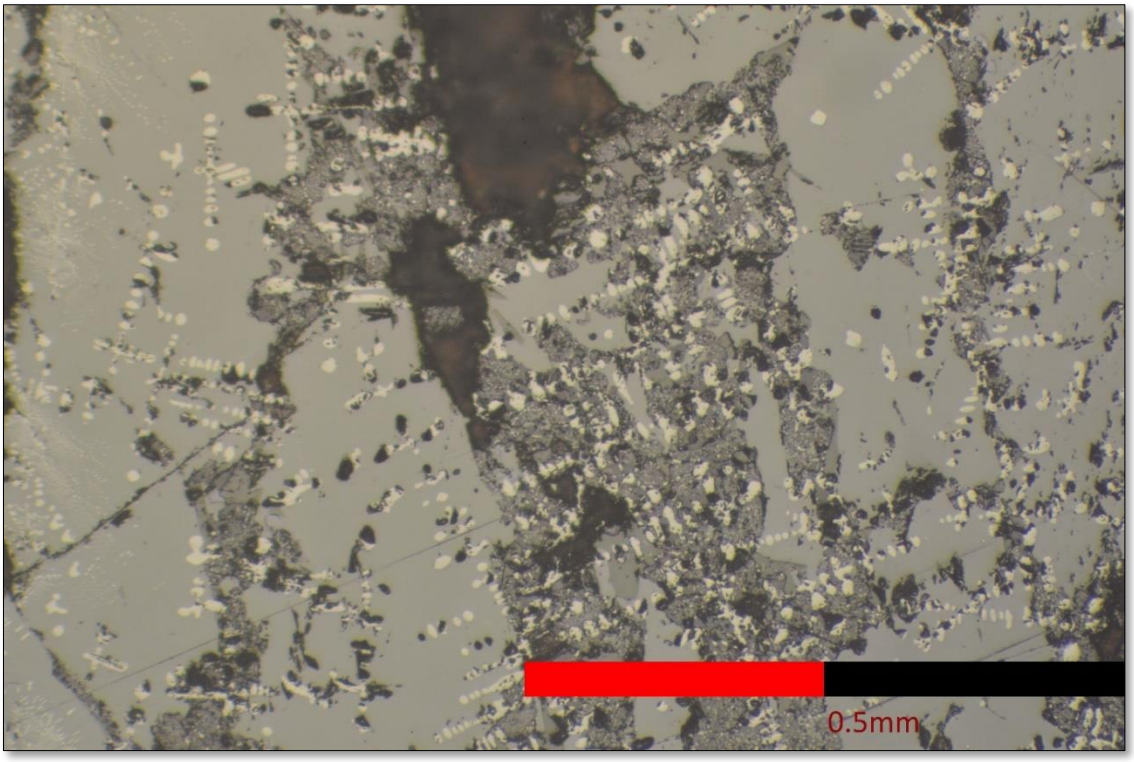

Plate 11, SES 263 375 Base - blocky fayalite and glass

The presence of Hercynite suggests either an ore with an elevated Alumina content or and increased contribution to the slag from the furnace lining.

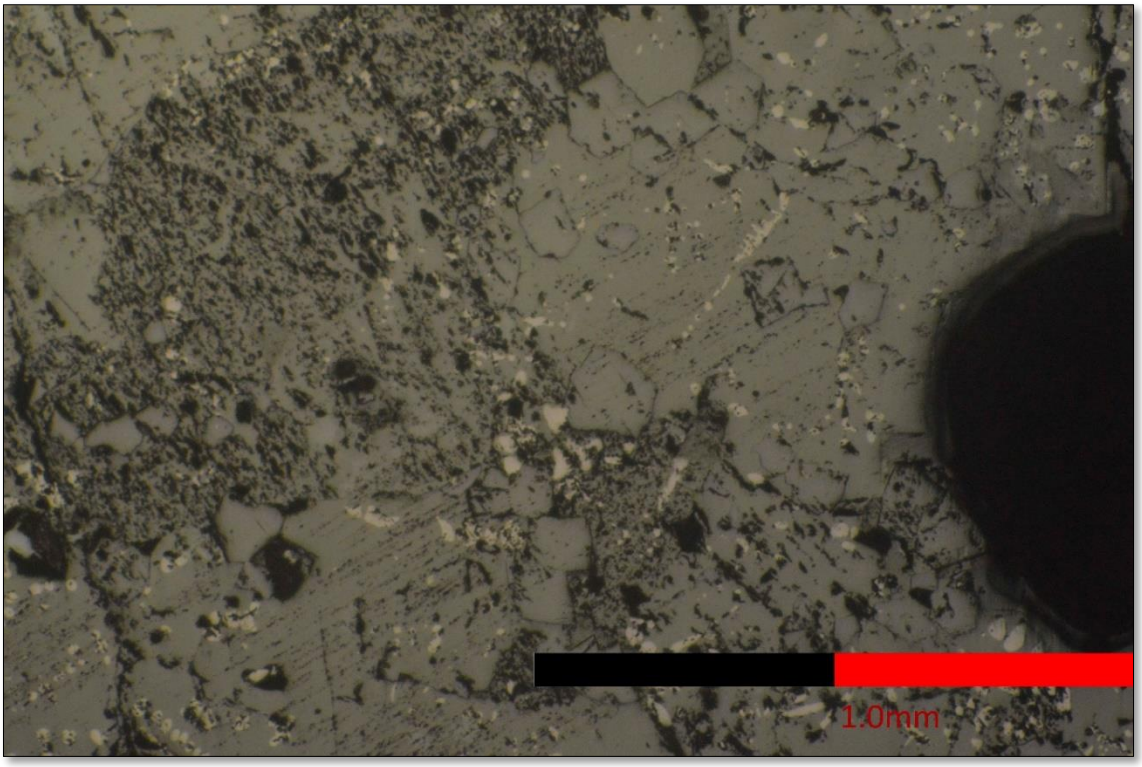

Plate 12, SES LM 4 - showing blocky fayalite and hercynite grains

As well as the sequential samples individual samples were taken from smaller fragments of slag. These reflect only a snapshot of the smelting process but there are consistencies within these samples. All have silicate in the form of fayalite, iron oxide in the form of wüstite and interstitial glass. The fayalite crystals are in lath form at the edges of samples leading to larger blockier silicate crystals in the centre of the samples.

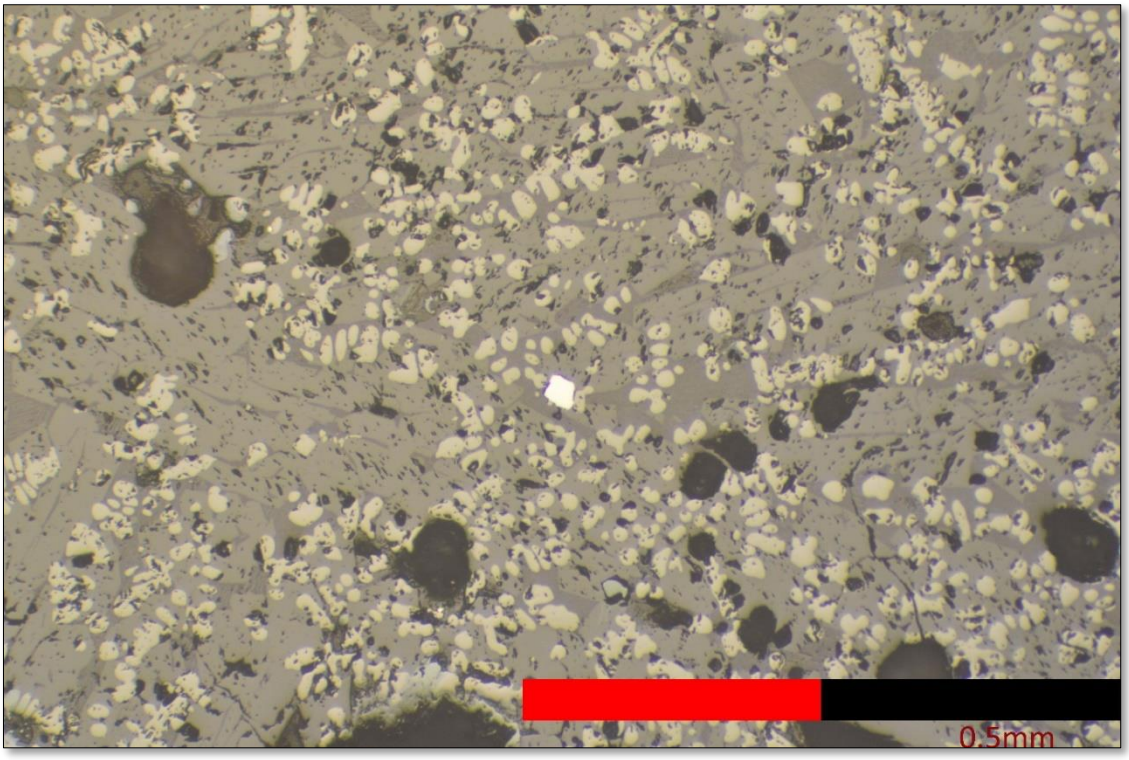

Plate 13, SES 32 95 - metallic prill and lath fayalite

'Life History'

By combining the macro and micro results from this chapter it is possible to determine that the smelting activity on this site used non-slag tapping furnaces but that these furnaces used different variations of this. The macro morphology shows that there were furnaces which were structurally different, the micro morphology shows that despite these different furnace structures the furnaces were still operated in a similar fashion. The non-slag tapping furnaces produced slag in which the fayalite crystals are in both the lath and blocky form. Laths being formed where the slag cooled more rapidly and the blocky fayalite where the slag was held between its liquidus and solidus temperature for longer allowing for the crystal growth. The presence of hercynite in some samples but not all suggests that there is a difference in the operation. The alumina needed for the production of this phase can be from either the ore or the furnace lining, the composition of the slag will reveal which of these is the case. The macromorphology of the samples from furnace 221 suggests that

the slag was quite liquid forming a solid block of slag, the micromorphology of these samples shows a low level of porosity. This would suggest that the slag either had a low viscosity close to its liquidus temperature or it solidified from a temperature significantly above its liquidus temperature. The slag from furnace 505 has much more porosity and trapped inclusions of charcoal and unreduced ore. The lower portions of the masses from this furnace have trapped inclusions indicating the smelt was not operating at full efficiency. The trapped inclusions and increased porosity are also an indicator that the slag may have been more viscous allowing for parts of the charge and bubbles of gas to be included. This lack of liquidity is an indicator that either the viscosity was high close to the melting temperature or the slag was not heated beyond its liquidus. These questions of viscosity and liquidus temperature will be addressed using the chemical analysis.

Chemical analysis

From the raw chemical composition of the slag it is possible to determine useful information about the smelting at this site. All the slag samples from this site have a high percentage of iron oxide (between c.55% and 70%) but it is within the expected range for iron smelting slag (Pleiner 2000, 252). None of the samples have a silica, magnesium or manganese level which would be considered high. The alumina levels are elevated but to a low level, similarly the calcium levels are low to very slightly elevated. The phosphorus levels are noticeable high, this suggests an impact from the ore rather than from the fuel ash. Given the location of the site the ore used on this site would have been bog ore. Bog ore contains a high level of phosphorus which splits between the slag and the metal during the smelt, the phosphorus that enters the metal directly affects the property of the metal. The phosphorus enters the iron lattice at the location which is normally occupied by carbon atoms. As they take the place of the carbon atoms in the lattice the presence of phosphorus hinders the uptake of carbon into the iron. As the phosphorus atoms are larger than the

carbon atoms they distort the iron lattice making it harder but also more brittle. Therefore, this site would have struggled to produce steel but would have produced phosphoric iron which could still be used for edged tools or weapons. As there is a low level of calcium and a moderate level of silica a higher proportion of the iron from the ore has to be sacrificed to flux the slag and allow it to flow away from the metallic iron during the smelt. The RII for the samples from this site are mostly either close to 1.0 or below 1.0 suggesting a more reducing atmosphere.

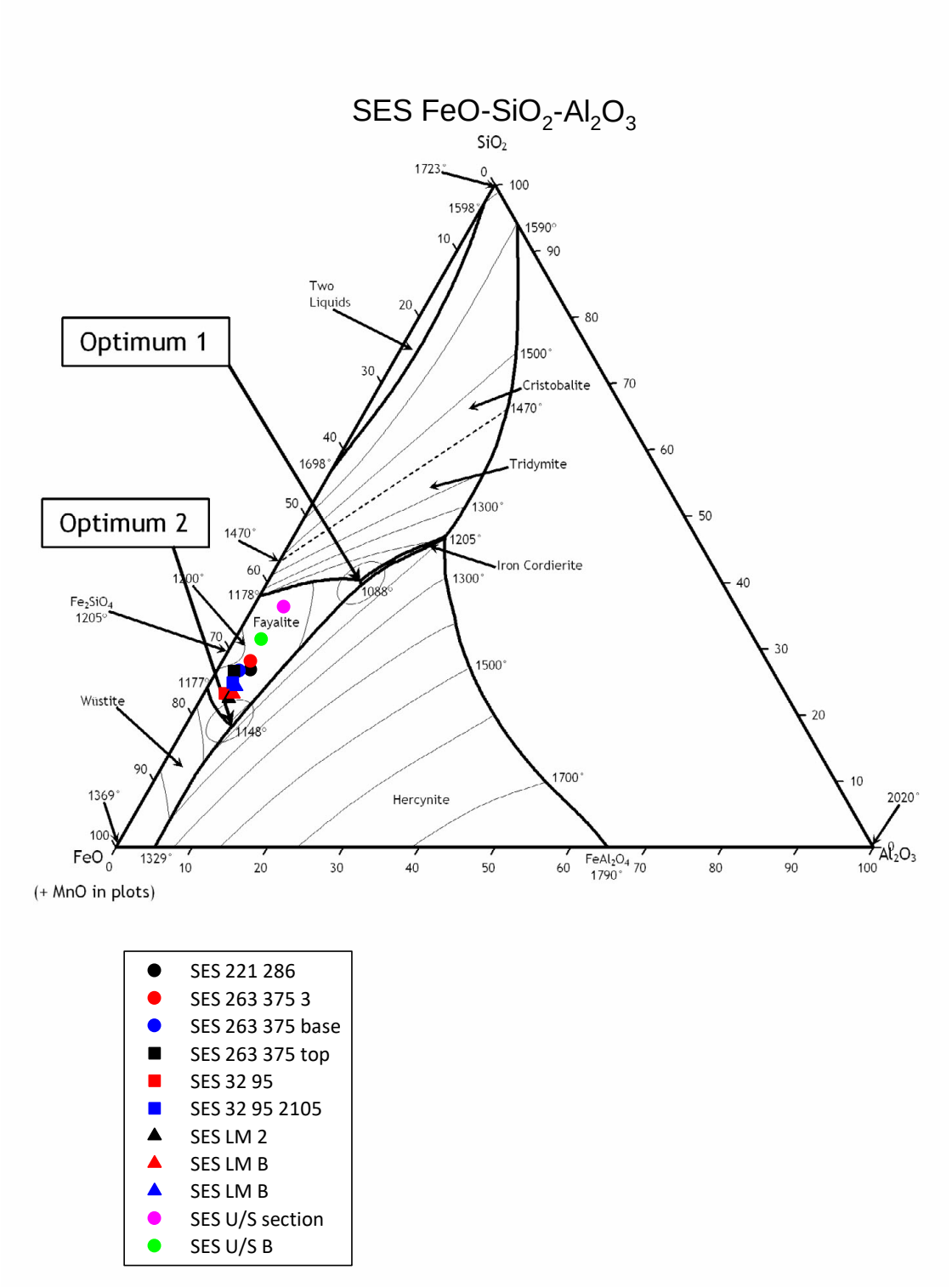

Figure 12, SES FeO-SiO_2-Al_2O_3 plot

By plotting the composition of the slag onto a FeO-SiO_2-Al_2O_3 phase diagram it is possible to estimate the liquidus temperature of the slag across this site between 1150 and 1200°C (Fig 12). Interestingly the smallest variation in the liquidus temperature is in the slag from

the same furnace but not the same smelt. This suggests the smelting process in each furnace was controlled to produce a slag with the same liquidus temperature. Using the Algoness slag viscosity calculator the viscosity of the slag across the 1150-1300°C range was calculated (Table 11, Fig. 13). The high proportion of iron oxide in most of the samples means they would have started to be free flowing at 1250°C.

SES sample	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
221 286 2015 1	0.9	0.5	4.2	24.4	3.8	0.8	2.4	b.d	b.d	63.5	100.5
263 375 3	b.d	0.5	3.7	26.0	3.1	1.5	2.0	b.d	0.4	63.3	100.4
263 375 base	b.d	0.4	3.0	24.9	2.5	1.3	1.7	b.d	0.3	66.1	100.1
263 375 top	b.d	0.4	2.4	25.3	1.9	0.9	1.0	b.d	0.3	68.1	100.2
32 95	0.5	0.4	2.7	21.2	3.7	0.9	2.5	b.d	0.4	68.1	100.6
32 95 2015	b.d	0.6	3.0	22.9	3.7	0.9	2.4	b.d	0.4	66.8	100.7
LM 2	b.d	0.4	3.6	20.9	4.5	0.6	1.1	b.d	0.4	69.2	100.7
LM B	b.d	0.5	4.0	22.1	2.5	0.8	0.5	b.d	0.2	70.3	100.9
LM TOP	b,d	0.4	3.6	22.3	4.3	1.2	1.7	b.d	b.d	66.9	100.3
U/S Section	b.d	b.d	3.8	33.1	4.2	2.0	2.1	b.d	0.4	54.5	100.1
US B	0.6	1.3	3.4	28.6	3.8	1.7	2.3	b.d	0.2	59.7	101.7

Table 10, SES composition

	1150°C	1200°C	1250°C	1300°C
SES 221 286	19.91	15.1	9.59	6.9
SES 263 375 3	23.66	17.6	11.33	8.14
SES 263 375 base	22.65	15.59	11.01	7.96
SES 263 375 top	23.82	16.47	11.67	8.47
SES 32 95	16.88	11.76	8.39	6.13
SES 32 95 2015	19.14	13.25	9.4	6.83
SES LM 2	18.06	12.51	8.89	6.47
SES LM B	28.88	19.92	14.09	10.2
SES LM TOP	19.42	13.37	9.45	6.8
SES U/S Section	35.16	23.2	15.75	10.97
SES US B	28.77	19.5	13.58	9.68

Table 11, SES viscosity in Poise

	RII
SES 221 286	0.92
SES 263 375 3	0.97
SES 263 375 base	0.90
SES 263 375 top	0.88
SES 32 95	0.74
SES 32 95 2015	0.81
SES LM 2	0.72
SES LM B	0.75
SES LM TOP	0.80
SES U/S Section	1.44
SES US B	1.14

Table 12 SES RII (green less reducing, red more reducing)

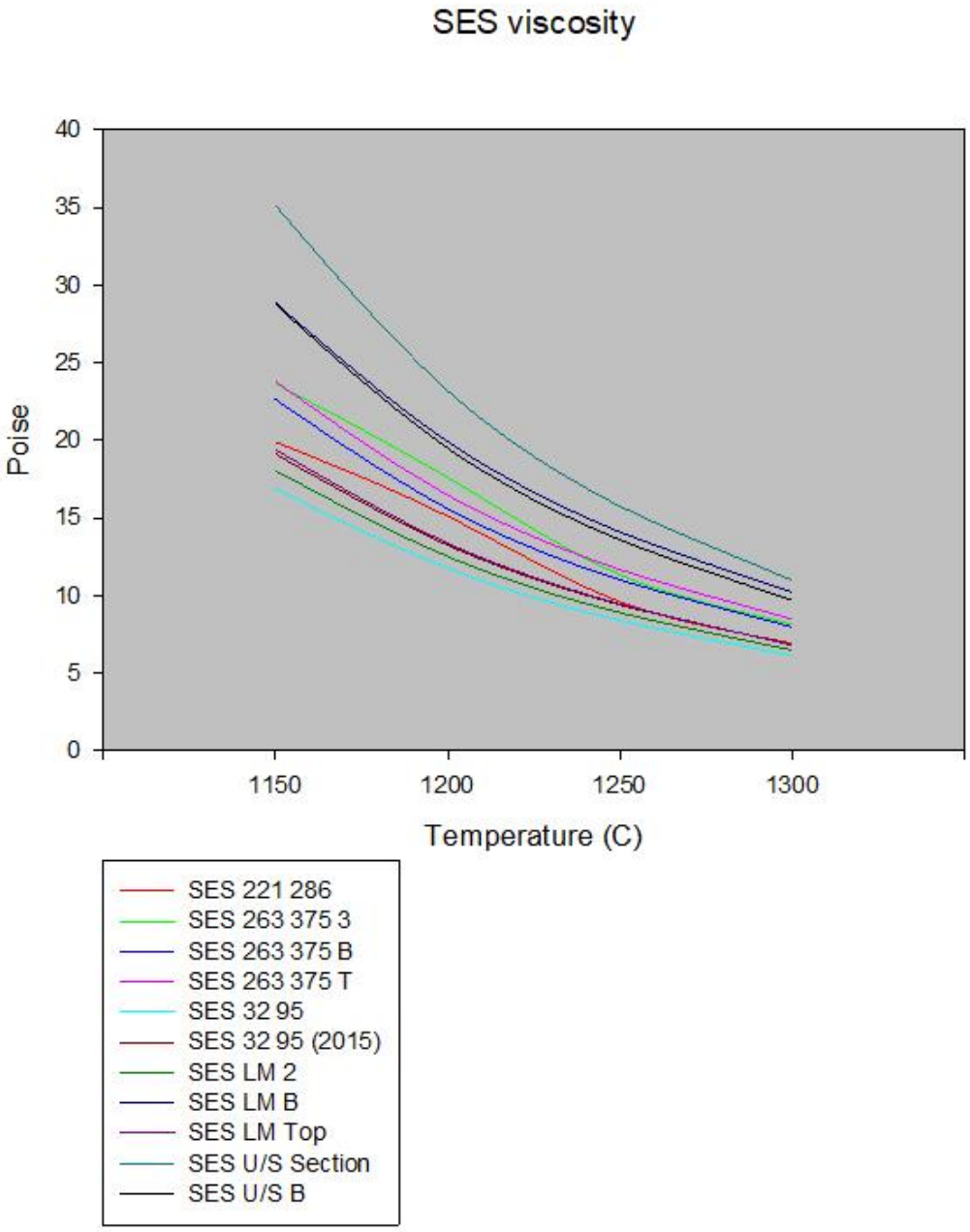

Figure 13, SES viscosity in Poise vs temperature (°C)

4.1.2 Grazeley Road, Reading, (GRR)

This site was a small unenclosed Iron Age settlement with a furnace accompanying one of the roundhouses. The slag was recovered from the gully surrounding the roundhouse which was dated to 760-503 cal BC from a radiocarbon date on charcoal securely positioned within the furnace. The site is a single smelting event on a settlement site.

Macromorphology

The small assemblage of slag recovered from this site is dominated by furnace slag as well as a small quantity of slag prills. None of the slag recovered has impressions of the furnace walls but the size of charcoal impressions allows the estimation of furnace size to be at least 0.3m. The prills are irregular in shape and have been formed by slag descending into and solidifying within the charcoal at the base of the furnace. They are a common slag type from suspected bowl furnaces such as those from Trevelgue Head (Dungworth 2011).

Plate 14 Prills from context 306

Plate 15 Furnace slag from context 306

Micromorphology

The small assemblage of slag from this site is thought to be from a single smelting event. The samples have silicate in the form of blocky fayalite, iron oxide in the form of wüstite and a glassy phase. As well as these fully formed phases there are samples which have partially formed slag which is identifiable by partially consumed mineral grains and substantial areas of glassy material.

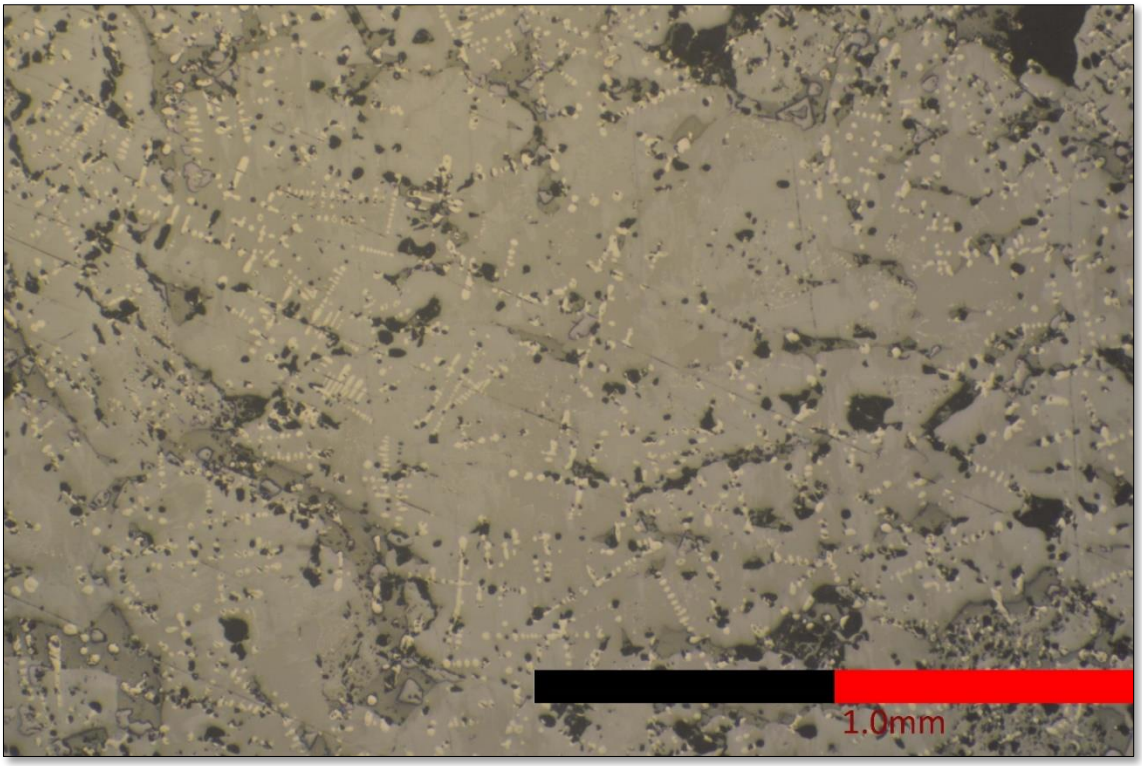

Plate 16, GRR 306 1 - blocky fayalite and interstitial glass

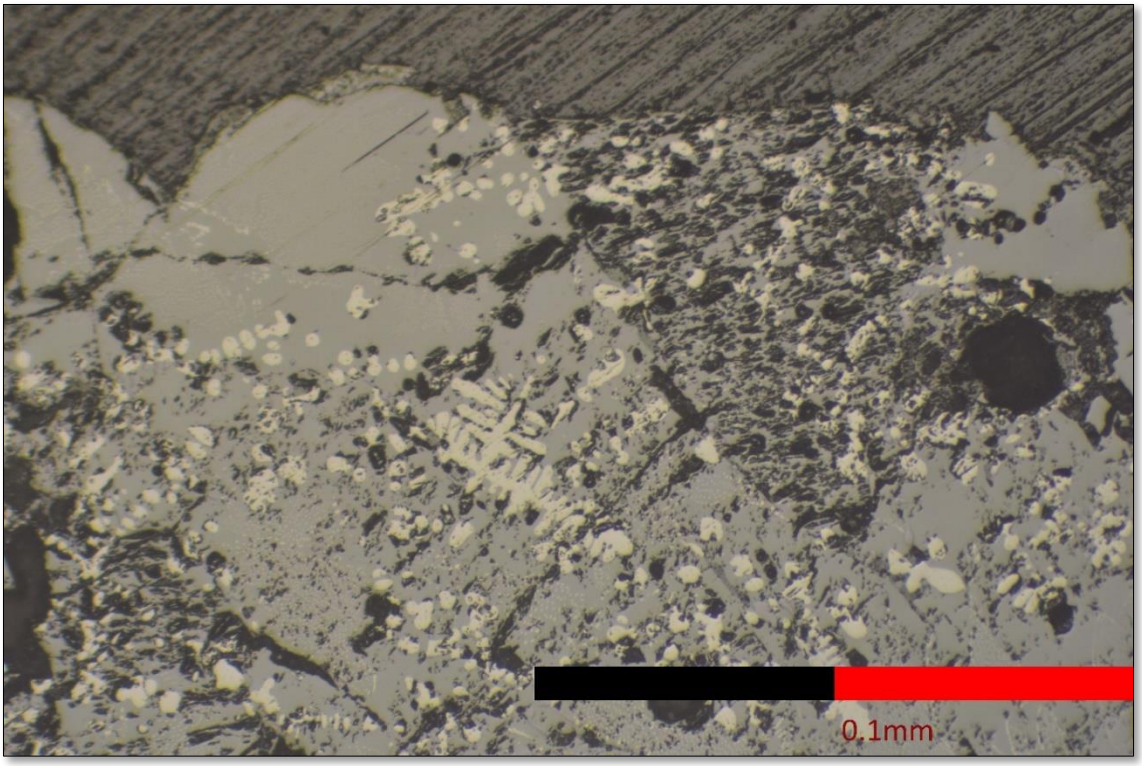

Plate 17, GRR 306 2 - developing blocky fayalite

The slag from this site has a microstructure which suggests that the smelting process which was carried out was not very effective in a number of ways. The number of samples which have a high proportion of partially formed mineral phases and high proportion of glass indicate that the process was halted abruptly while ore and charcoal were still being added. This suggests a smelt that either rapidly formed a bloom and could be halted or more likely was halted due to excessive production of slag which filled the furnace.

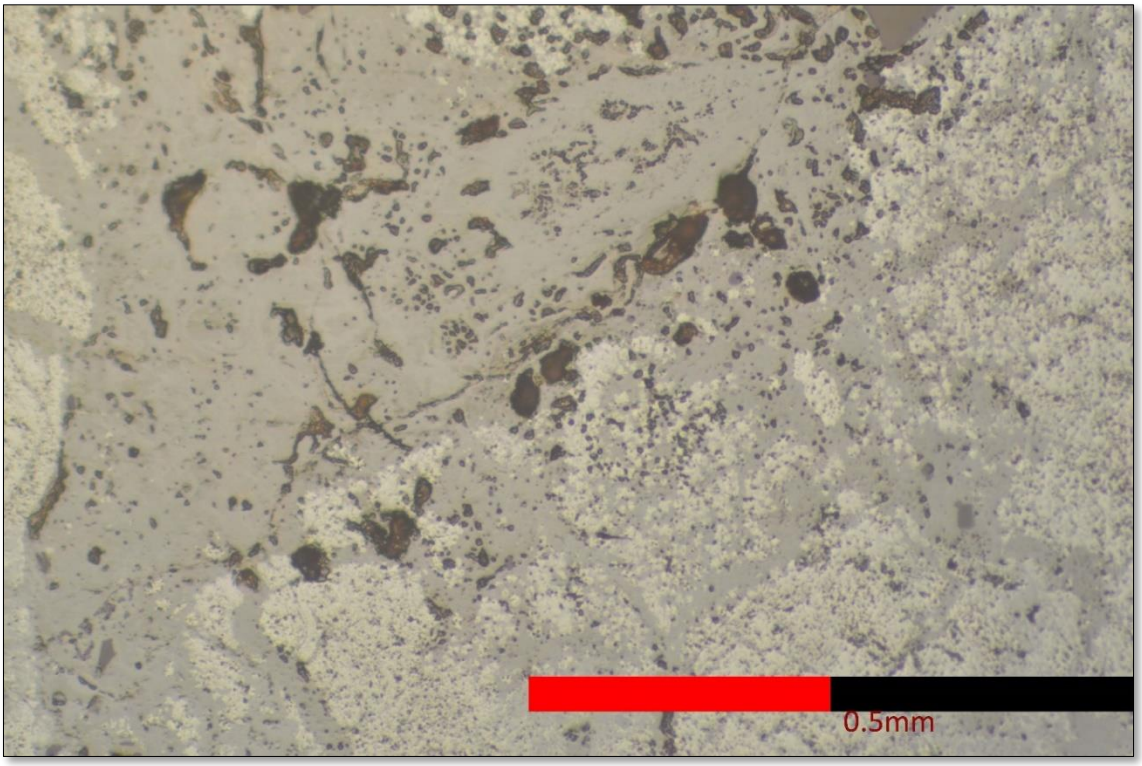

Plate 18, GRR 421 1 - partially formed slag and partially reduced ores

'Life history'

The macromorphology combined with the micromorphology of the slag from this site suggests that a small scale non-slag tapping smelt was in operation. The small prills of slag (micrographs not shown due to poor image quality) which formed within the bed of charcoal at the base of the furnace have a microstructure dominated by silicate laths indicating they solidified over a short thermal gradient. The larger masses of furnace slag

which the macromorphological indicates would have been above the unburnt fuel were held at a high enough temperature to allow for the full growth of the silicate into a blocky form. However, the microstructure of some of the slag also indicates that at some stage smelt was not at a suitable temperature for complete slag formation. This may have been the result of the smelt being halted early. The chemical analysis will show whether the liquidus temperature of the slag was part of the reason why the slag was not fully formed.

Chemical composition

All of the samples from this site have a high level of iron oxide (67-76%) one of these samples is outside the normal range for iron oxide (Pleiner 2000, 252). However, this can be explained by the presence of partially reduced ore fragments which have a higher iron content than the surrounding slag. The phosphorus levels are noticeable high suggesting an input from the ore and indicating that bog ore was being used at this site, this would have the same effect on the metal as described above for SES. As there is a low level of calcium and moderate level of silica therefore a higher proportion of iron has to be maintained in the slag as a flux.

Using the FeO-SiO_2-Al_2O_3 phase diagram the liquidus temperatures of the slag from this site are clustered around 1200°C. It is interesting how despite quite different compositions the liquidus temperatures are very similar. The samples from this site would have begun to be free flowing at 1250°C (Fig. 17). The RII of the slag from this site indicates that the furnace was less reducing and had quite consistent reducing conditions.

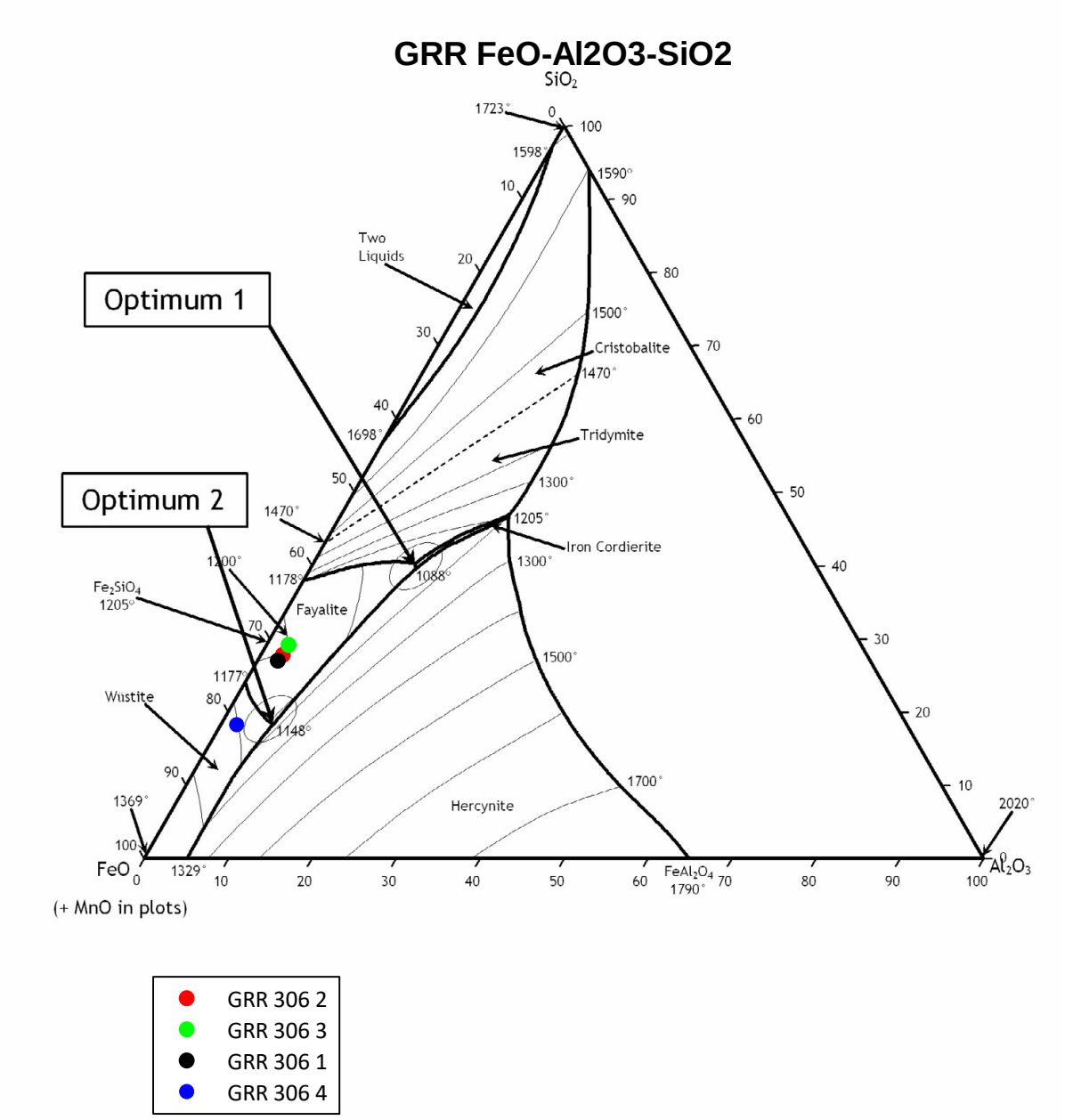

Figure 14, GRR FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
GRR 306 2	b.d	b.d	2.6	23.8	2.6	b.d	0.5	b.d	0.5	69.9	99.9
GRR 306 2.2	0.8	0.4	2.8	24.3	2.3	0.3	0.6	b.d	0.5	69.8	101.8
GRR 306 4	0.6	b.d	1.9	17.5	2.7	b.d	0.8	b.d	0.7	76.5	100.8
GRR 306 3	0.7	0.4	2.8	23.1	3.8	0.5	1.2	b.d	0.5	67.6	100.4

Table 13, GRR composition

	1150°C	1200°C	1250°C	1300°C	1350°C
GRR 306 2	29.12	20.08	14.25	10.34	7.66
GRR 306 3	22.09	15.73	11.16	8.1	6
GRR 306 1	24.15	16.29	11.57	8.4	6.23
GRR 306 4	16.47	11.7	8.51	6.32	4.79

Table 14, GRR viscosity in Poise

	RII
GRR 306 2	0.81
GRR 306 3	0.83
GRR 306 1	0.54
GRR 306 4	0.81

Table 15, GRR RII (green - less reducing, red – more reducing)

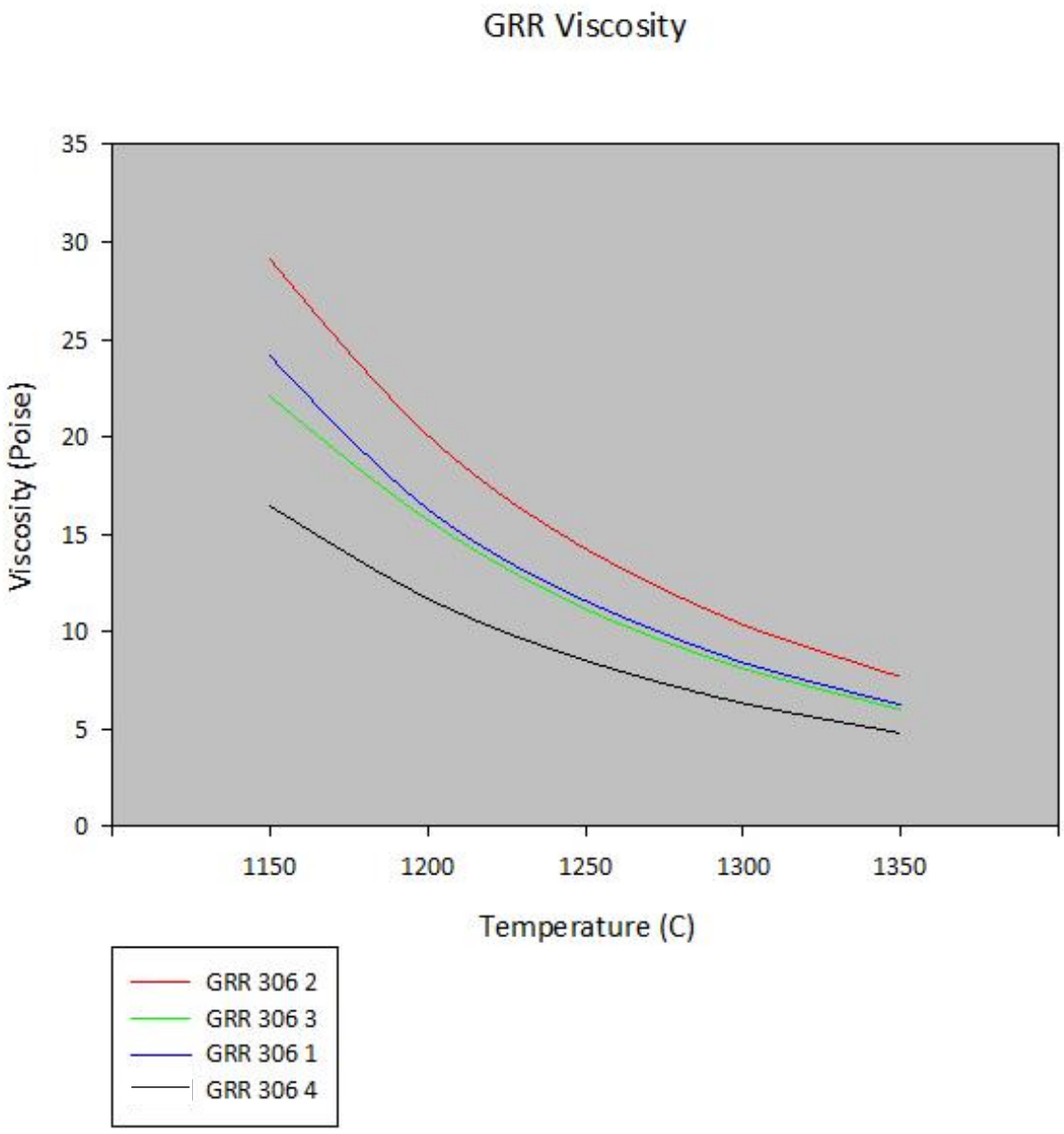

Figure 15, GRR Viscosity (Poise) vs temperature (°C)

4.1.3 Manor Farm, Finchampstead (MFF)

This site was excavated as part of a small archaeological observation, the smelting activity was dated to 407-357 cal BC. There was a single possible furnace uncovered which suggests an isolated smelting site, but there is a slag heap further to the north in land which was not excavated. Without further work into this feature it cannot be said for certain of the scale of this site.

Macromorphology

The slag from this site has main two forms, small prills and larger masses. The larger masses of slag have impressions of wood, not fissured or fractured as can be commonly observed in charcoal or charred wood. These impressions of both round and square split wood suggests that the furnace had a bed of wood which supported the charge in the furnace. The fragments of furnace slag do not have any impressions or shape of the furnace structure and as no furnace structure was excavated we cannot be sure of the exact furnace design. The suggestion of the charge being supported above the base of the furnace suggests that the airblast was located away from the base of the furnace. This suggests that to have enough space for this it would have been a shaft furnace.

Plate 19, Prills from context 9

Plate 20, Furnace slag from context 15

Micromorphology

The assemblage of slag from this site is thought to be from a single smelting event the microstructures support this theory. They are consistent with what may be produced from a single smelt. Three main phases are present, fayalite, wüstite and an interstitial glassy phase, there is also very occasional metallic prills in two of the samples. The fayalite is present as blocky grains or large blocky laths, the first of these suggests the slag was cooled over a long thermal gradient which led to the formation of equiaxed grains. The blocky laths indicate that the slag cooled slowly enough for the silicate laths to grow more blocky than elongated. The wüstite present in these samples is mostly in dendritic form but also in isolated crystals. The amount of wüstite present is quite low which suggests a more reducing atmosphere in the furnace. This would have resulted in more iron potentially being reduced from the ore. Unfortunately the metallic prills present in this sample are too small to be etched to reveal the microstructure of the iron trapped within. All of the prills are small and globular in form.

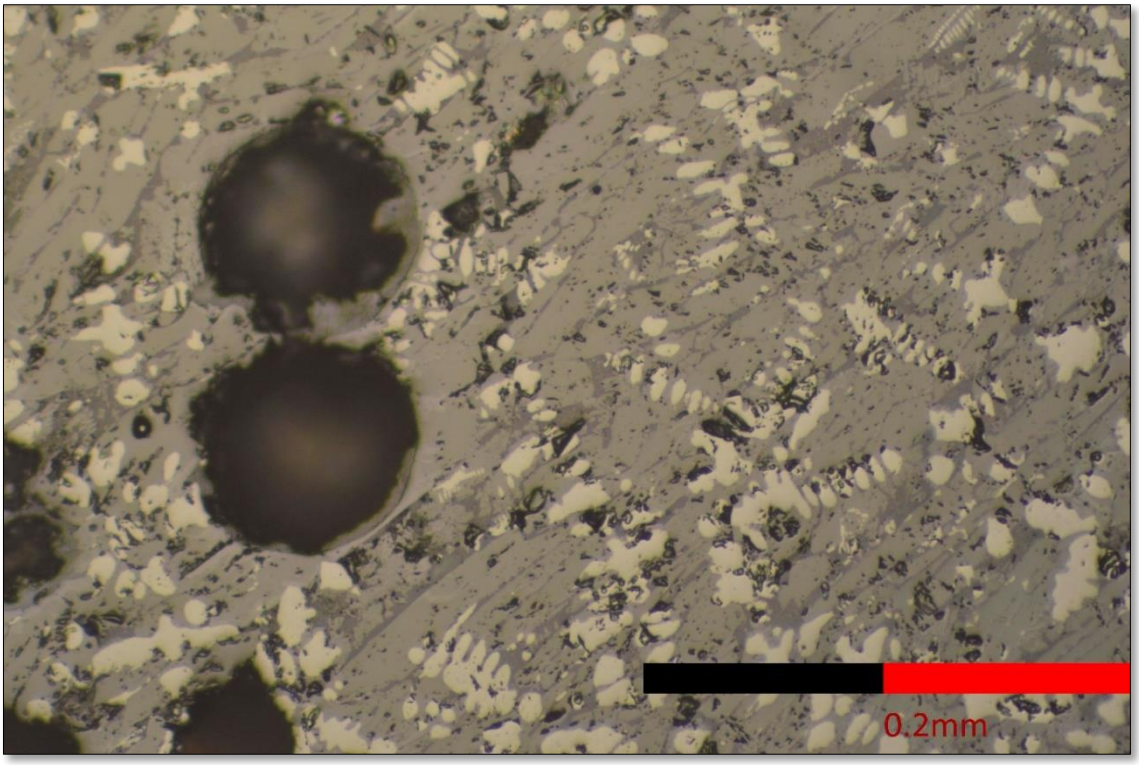

Plate 21, MFF 15.1 fayalite laths

The microstructure of the slag from this site indicates that the smelting process being carried out was consistent during the smelt. The low levels of free iron oxide in the form of wüstite indicate that the conditions in the furnace were quite reducing and that this would lead to more of the iron oxide from the ore being reduced to metallic iron. This may have also produced more steely iron but there are chemical factors which will also affect this. The negative factor to the higher proportion of iron from the ore is that the slag would have had increased viscosity compared to one that had more iron oxide present. The structure of the silicate indicates this slag was held above its solidus temperature at a constant level to allow the formation of blocky rather than lath silicate.

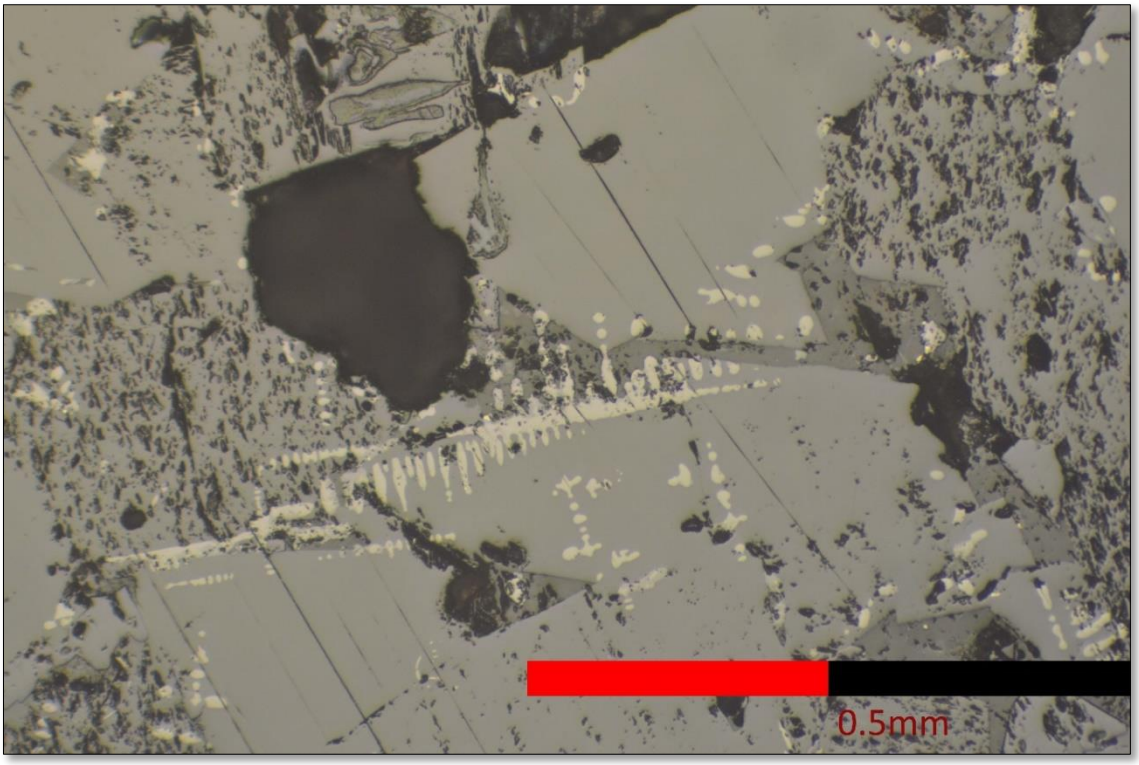

Plate 22, MFF 15.2 blocky fayalite

'Life History'

The combination of the macro and micromorphology of the slag from this site suggests that non-slag tapping furnace was in operation and that there was likely one furnace in operation as the variation in the slag is within the range which would be expected for a single furnace. The slag which has formed over and around pieces of wood would have been quite viscous this may be because of a high viscosity close to its liquidus temperature or because of a high liquidus temperature. The blocky fayalite indicates that the slag was cooled over a long thermal gradient this suggests the slag was held at a high enough temperature to allow for the growth of blocky silicate grains. The fragments of slagged lining show that the slag was in contact with the furnace lining between its liquidus and solidus temperature for a prolonged period allowing for the slag to attack the lining and

the growth of the larger fayalite crystals. The viscosity and melting temperatures of the slag will be addressed using the chemical analysis.

Chemical composition

The samples from this site are dominated by a high level of iron oxide being very close to the upper limits described by Pleiner (2000, 252). The silica levels are towards the lower end of the expected composition. The alumina levels are very slightly elevated but the calcium levels are low suggesting these two are not related and therefore the elevated alumina is from increased contribution from the furnace lining. The phosphorus levels are elevated which suggests an ore with a high level of phosphorus and most likely bog ore. The effect of this on the metal will be the same as at SES, GRR and MGE.

The estimated liquidus temperature of the slag from this site is closely clustered around 1200°C (Fig. 16). The low level of alumina means the composition of the slag plots very closely to the composition of pure fayalite. The viscosity of all the samples from this site plot closely together suggesting they were produced from the same furnace. They were all quite free flowing at a temperature close to their liquidus and become very free flowing above this. The RII of the slag from this site indicates the furnace was less reducing.

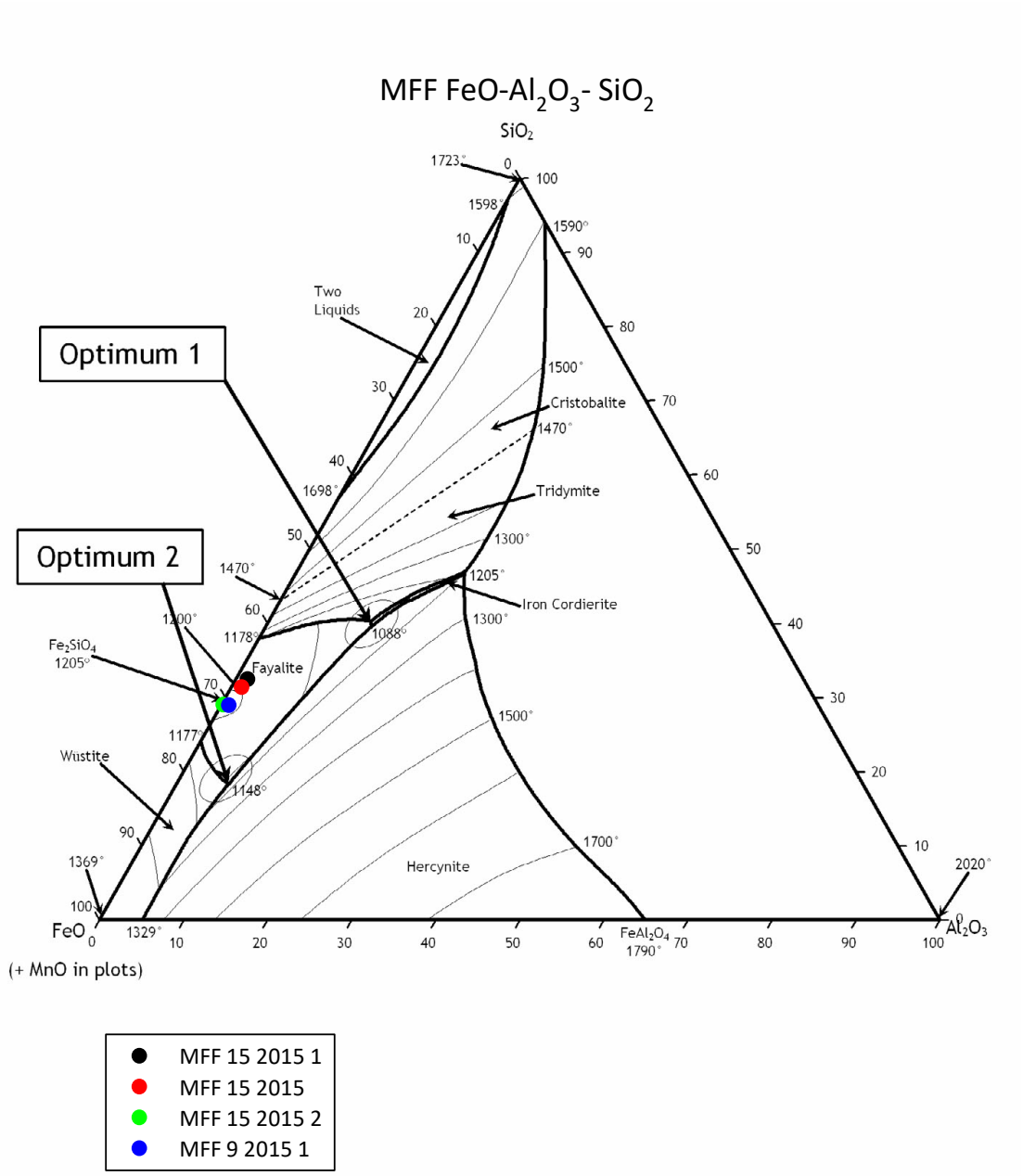

Figure 16, MFF FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
MFF 15 2015 1	b.d	b.d	2.2	25.6	4.5	0.5	1.2	b.d	b.d	66.1	100.1
MFF 15 2015	b.d	b.d	2.0	25.5	3.9	0.5	0.9	b.d	0.3	67.3	100.5
MFF 15 2015 2	b.d	0.4	1.0	22.0	4.3	0.2	1.8	b.d	0.3	70.2	100.4
MFF 9.1	b.d	b.d	1.9	22.8	4.0	0.4	1.3	b.d	b.d	69.7	100.0
MFF 9 2015 1	b.d	b.d	1.7	23.5	3.5	0.3	1.1	b.d	0.4	69.9	100.4

Table 16 MFF composition

	1150°C	1200°C	1250°C	1300°C	1350°C
MFF 15 2015 1	15.77	10.86	7.66	5.54	4.08
MFF 15 2015	19.92	13.24	9.4	6.82	5.06
MFF 15 2015 2	14.97	10.81	7.78	5.73	4.3
MFF 9 2015 1	16.64	11.15	8	5.87	4.4

Table 17, MFF Viscosity (Poise)

	RII
MFF 15 2015 1	0.93
MFF 15 2015	0.90
MFF 15 2015 2	0.75
MFF 9 2015 1	0.78

Table 18, MFF RII (green – less reducing, red – more reducing)

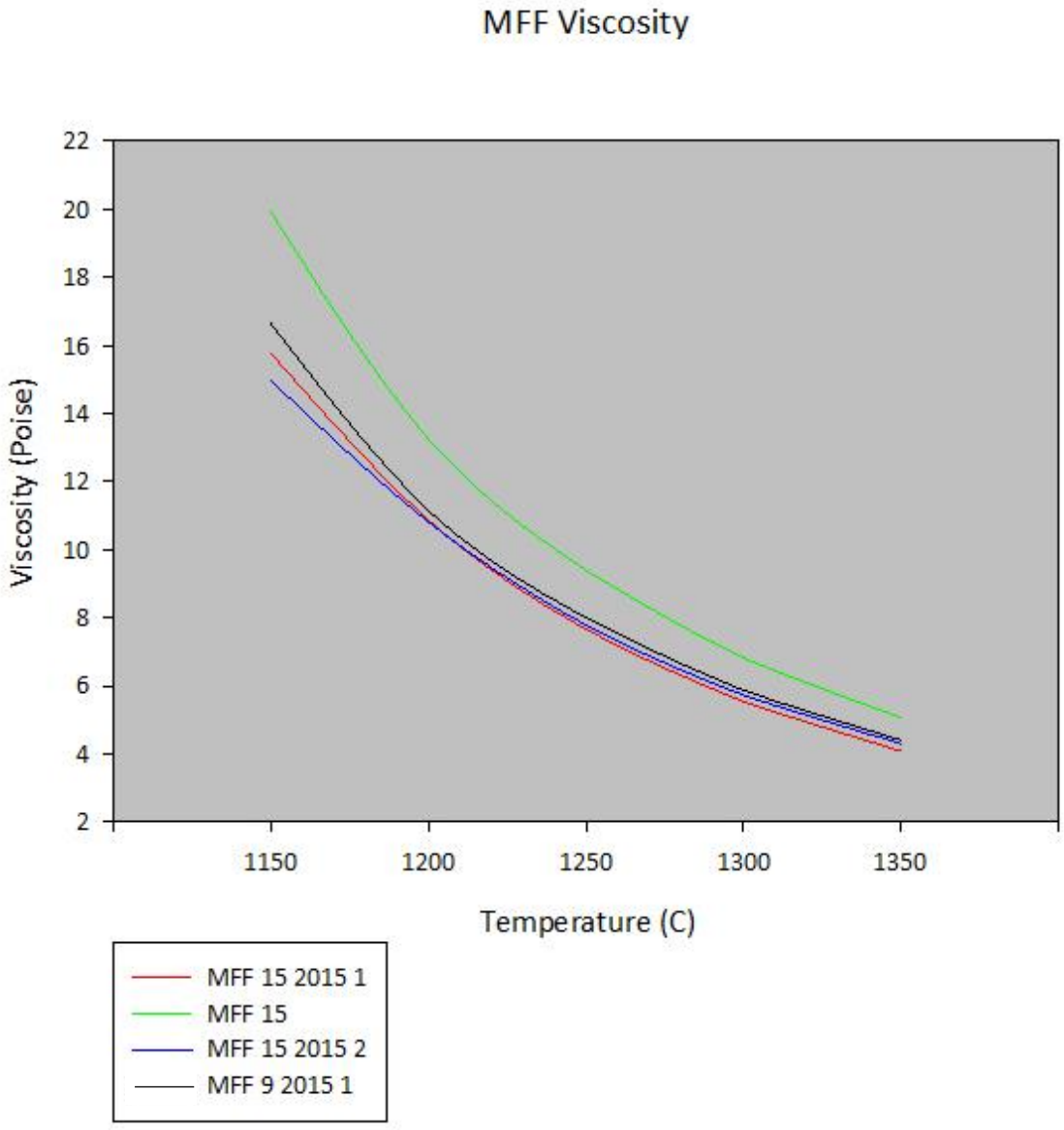

Figure 17, MFF Viscosity (Poise) vs Temperature (°C)

4.1.4 Hartshill Copse, Upper Bucklebury (HCB)

This site was excavated in advance of gravel extraction, the samples examined here are from a later excavation phase than the evidence for iron smithing (Collard *et al.* 2006) discussed early. Smelting evidence from earlier phases has been dated to the 5th and 6th centuries BC (Brett *et al.* 2004). The later phase of excavation studied here uncovered the in-situ furnace bottom which is being studied here. The site is a small settlement site with different phases of small scale smelting activity.

Macromorphology

The available assemblage from this site consisted of a single large furnace base, fractured upon lifting into three sections, all of which were present. The mass weighed 30kg and measured 400mm by 450mm. It has a large amount of included charcoal and impressions of wood.

Plate 23, Wood impressions in slag mass

The form of the slag shows the furnace was roughly circular with vertical walls, the front portion of the mass has some evidence for damage and flow away from the bulk of the mass. This would suggest that the front of the furnace was removed to access the iron bloom. The mass appears to be in three areas, large dense areas, small dense runs and porous areas. The dense areas were formed at the base and some of the side of the mass by liquid slag descending to the base of the furnace. The smaller dense runs are the result of more viscous slag descending through the furnace and the charge and are loosely connected to the rest of the mass. The more porous slag has been formed by the slag solidifying over charcoal which was then burnt away which suggests that at this point there was a large part of the charge descended into the slag mass at the base of the furnace. The upper surface of the mass was rough indicating that fragments of slag and possibly the bloom were removed from the upper surface rather than being completely separate. This along with the shape of the furnace suggests that it was not a slag pit furnace where the mass of slag would be separate. This is likely to be the result of a single smelting event.

Plate 24, Half of slag block from context 3634

Micromorphology

As these samples were taken from the same mass of furnace bottom slag there should be certain similarities between them but there could be variation caused by the point in the smelt the slag was formed and solidified. The microstructure of this slag has three main phases, fayalite, wüstite and interstitial glass, minor phases include metallic prills and hercynite. The silicate crystals vary in form between the samples. HCB 3634 1 has fine silicate laths, whose needle like structure suggests they cooled rapidly.

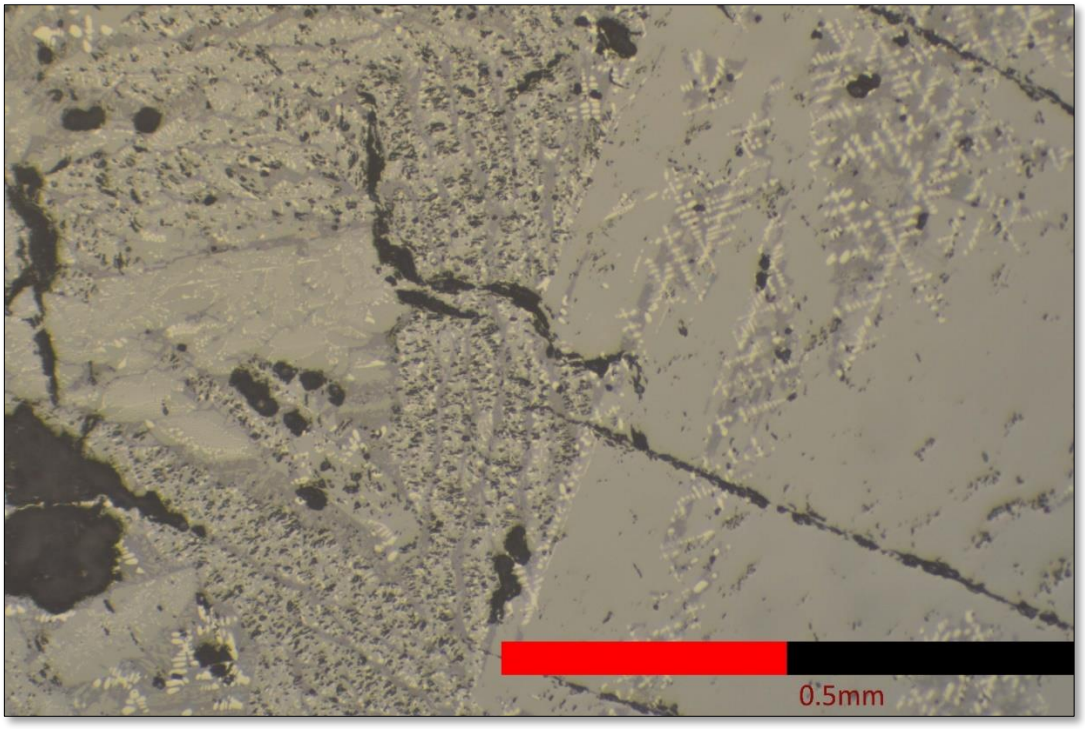

Plate 25, HCB 3634 1, fine and blocky fayalite laths

As this slag was not removed from the furnace the structure created by rapid cooling is a result of the smelt halting rather than the slag being exposed to cooler air. The other samples all have large blocky fayalite crystals indicating that they were held at a high enough temperature to allow full growth of the crystals. The volume and form of the wüstite varies between the samples indicating there was variation in the reduction conditions throughout the smelt and the temperature. The variation in temperature has affected the formation of the wüstite, the variations were within the liquidus solidus gap of the fayalite. The wüstite varies from fine skeletal dendrites to larger more globular dendrites, relating to a faster to slower cooling rate of the slag. The microstructure of the slag from this site indicates that although the slag was cooled slowly enough to form blocky silicate however there was variation in the temperature and reduction conditions. There is the possibility that there were inconsistencies with the charging of the furnace.

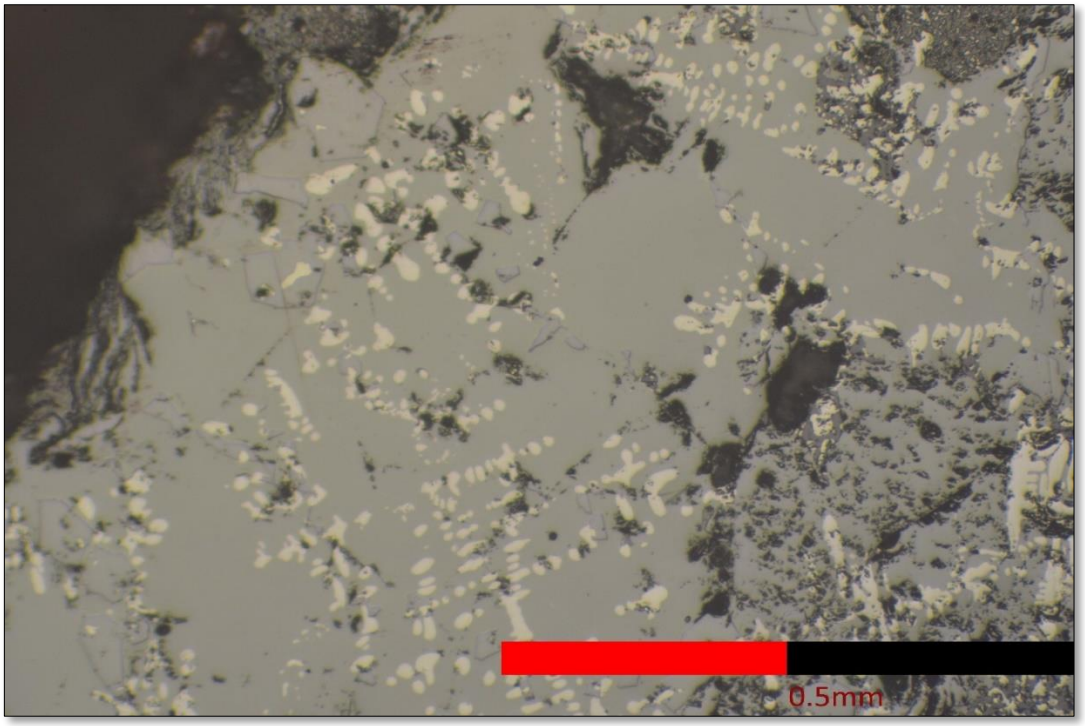

Plate 26, HCB 3634 2, fine hercynite crystals and blocky fayalite

The presence of hercynite in one sample indicates an increase input of alumina either from the ore showing an increase in ore or an increased input from the lining of the furnace. The difference between these two should be identifiable through the chemical analysis.

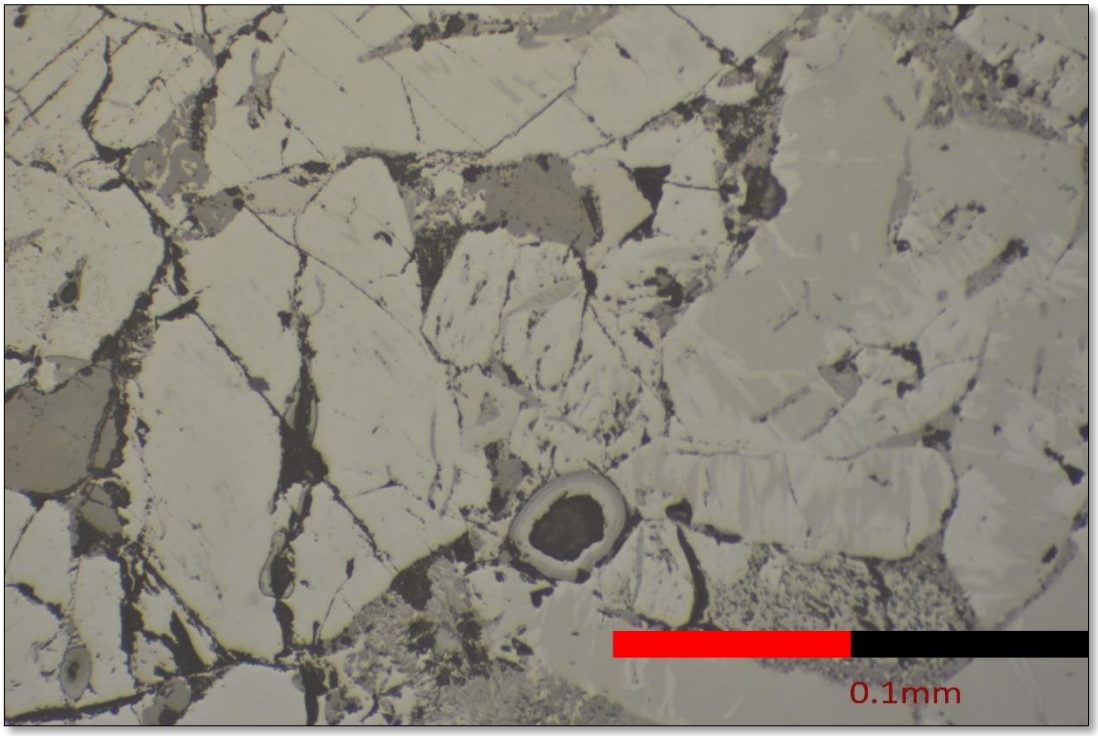

Plate 27, HCB 3634 5, low FeOx slag

'Life history'

While all of the samples are from the same mass it may have been the result of the accumulation of slag from multiple smelts. However, the macro and micromorphology of the slag from this site indicate that all the samples are the result of a single smelt. The chemical analysis of these samples will reveal whether there was variation in the inputs or conditions changes during the smelt. The presence of hercynite in the micromorphology will be examined using the chemical analysis to see whether the input of alumina to form this is from the ore or from the furnace lining. The lower portions of this mass have a fine lath structure and have trapped fragments of charcoal and ore. The lower temperature of the lower portion of the furnace where the charcoal and ore were not burnt or reduced meant that the slag was cooled over a shorter thermal gradient and with more opportunities for freeze surfaces to begin. The slight changes in the microstructure through the mass are not as obvious in the macro morphology as the exterior surface of the mass is quite similar and made of a series of small runs. The chemical analysis will be targeted at identifying

the changes in the smelting conditions and possible changes in the inputs to the smelt. For example is the presence of hercynite the result of an increase in the ratio of ore to fuel or increased interaction with the furnace lining.

Chemical composition

All of the samples have a high iron oxide content but within the predicted range for direct smelting slag. They also have elevated levels of alumina but not high levels and low level of calcium which would suggest that this was contributed from the furnace lining rather than the ore. The phosphorus levels are not high suggesting that the ore being used at this site was not a high phosphorus ore such as bog ore. The low level of calcium and moderate levels of silica mean that more of the iron had to be sacrificed into the slag as a flux limiting the quantity of metal which could potentially be reduced from the ore.

The liquidus temperature of the slag from this site is consistent between 1150- 1175°C. This indicates that the inputs to the smelt were consistent throughout the single smelt these samples represent. The viscosity of the slag is quite high and it would have been required to heat the slag to around 1300°C to become free flowing.

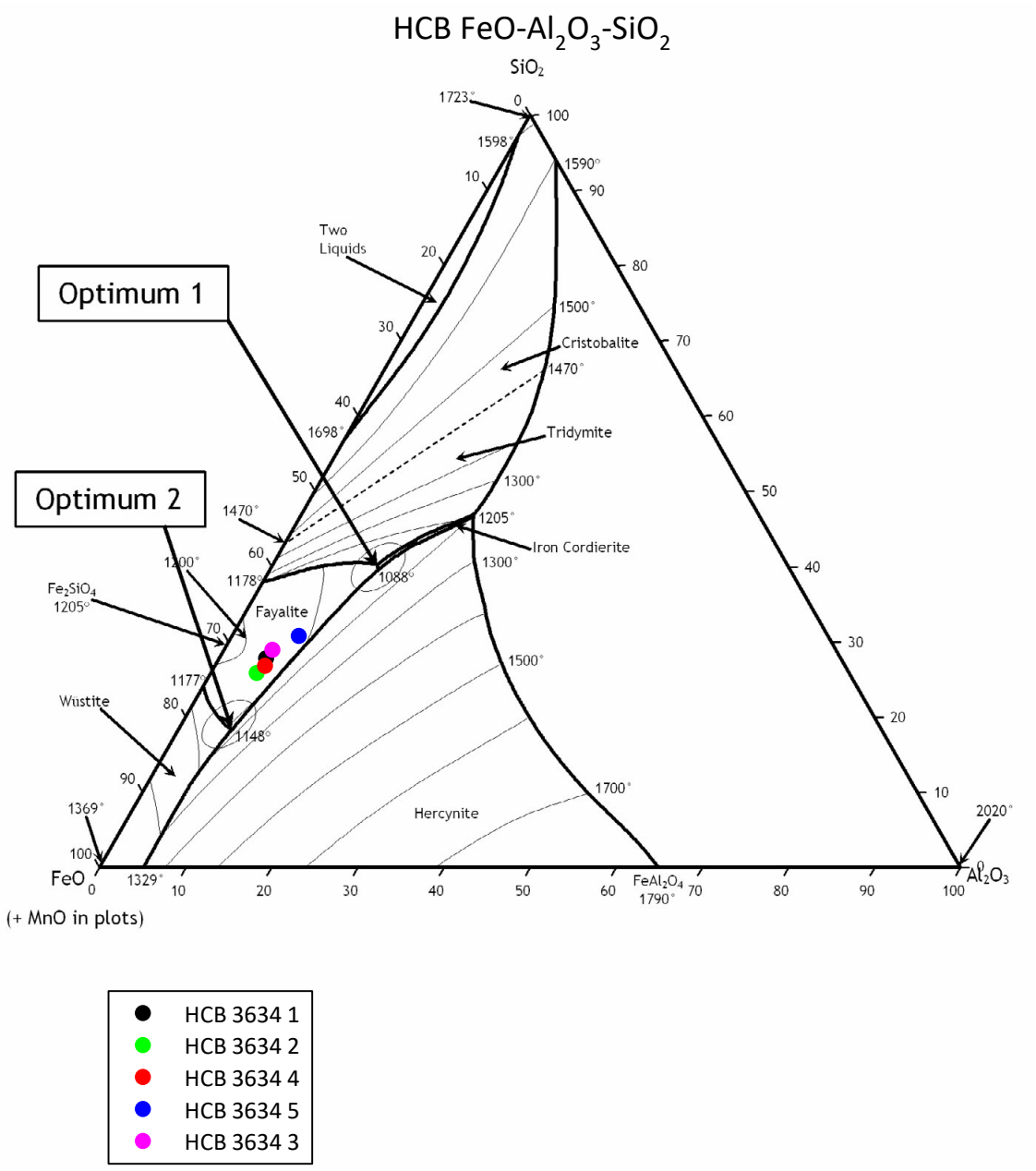

Figure 18, HCB FeO-Al2O3-SiO2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
HCB 3634 1	b.d	b.d	5.3	27.0	1.0	1.3	0.9	b.d	1.2	63.4	100.0
HCB 3634 2	b.d	0.5	5.1	25.1	1.2	0.6	1.2	0.3	1.0	65.4	100.5
HCB 3634 4	b.d	0.4	5.6	25.9	1.4	0.7	1.2	b.d	1.0	63.9	100.3
HCB 3634 5	0.6	0.4	7.3	29.2	1.8	0.9	1.7	0.4	1.0	57.2	100.6
HCB 3634 3	0.6	0.5	5.4	28.0	1.2	0.8	1.0	b.d	1.2	61.9	100.6

Table 19, HCB composition

	1150°C	1200°C	1250°C	1300°C	1350°C
HCB 3634 1	41.16	27.8	19.3	13.48	9.78
HCB 3634 2	36.2	24.59	17.15	12	8.7
HCB 3634 4	38.65	26.08	18.07	12.83	9.31
HCB 3634 5	46.06	30.6	20.91	16.21	11.52
HCB 3634 3	46.53	31.24	21.56	15.15	10.95

Table 20, HCB viscosity in Poise

	RII
HCB 3634 1	1.00
HCB 3634 2	0.90
HCB 3634 4	0.96
HCB 3634 5	1.20
HCB 3634 3	1.06

Table 21, HCB RII (green – less reducing, red – more reducing)

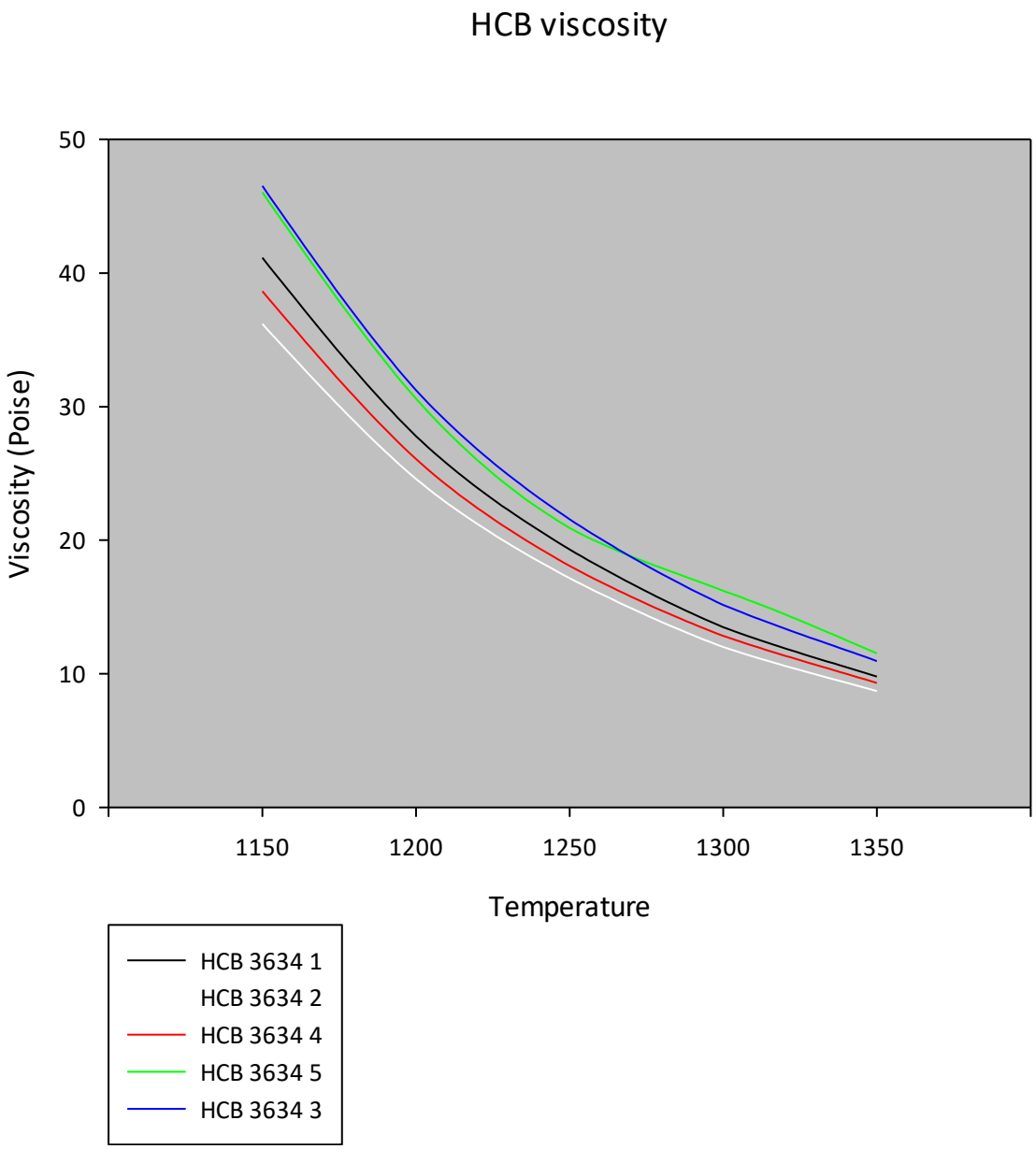

Figure 19, HCB Viscosity (Poise) vs Temperature (°C)

4.1.5 Matthew's Green, Wokingham (MGE)

A small middle Iron Age settlement was excavated in advance of a housing development. The slag was excavated from a ring gully dated to 541-392 cal BC and 397-208 cal BC. This site is a small settlement site with small scale smelting activity.

Macromorphology

The assemblage from this site was dominated by furnace slag but there were also fragments with evidence for higher liquidity in the form of sheet slag. The size of the furnace is likely to have been around 0.2-0.3m in diameter based on the form of one of the fragments of furnace slag. The dominance of furnace slag in the assemblage suggests a non-slag tapping furnace. The fragments with evidence for more liquidity may represent a final stage of the smelt where the temperature of the furnace was increased to separate the slag from the metal.

Plate 28, Furnace slag with trapped charcoal

Micromorphology

There are three main phases present in the samples from this site however there is still considerable variation within the amount and form of the fayalite and wüstite. The fayalite is present in both lath and blocky forms, this indicates some samples were cooled rapidly and some were cooled more slowly or even held at a stable temperature which allowed the fayalite to grow into a blocky form. The wüstite is present as dendrites in most samples but there are also some samples with large areas of iron oxide which are fragments of partially reduced ore. The amount of wüstite varies between samples this indicates differences in the amount of reducing gases available and therefore the amount of iron oxide from the ore which could be reduced to metallic iron. The changes in this suggests this process was not well controlled and that there was substantial variation in amount of reducing gases or that there was substantial difference between smelting events. The microstructure of the slag from this site suggests that the smelting process was not finely controlled as there is substantial differences in the reducing conditions during smelts.

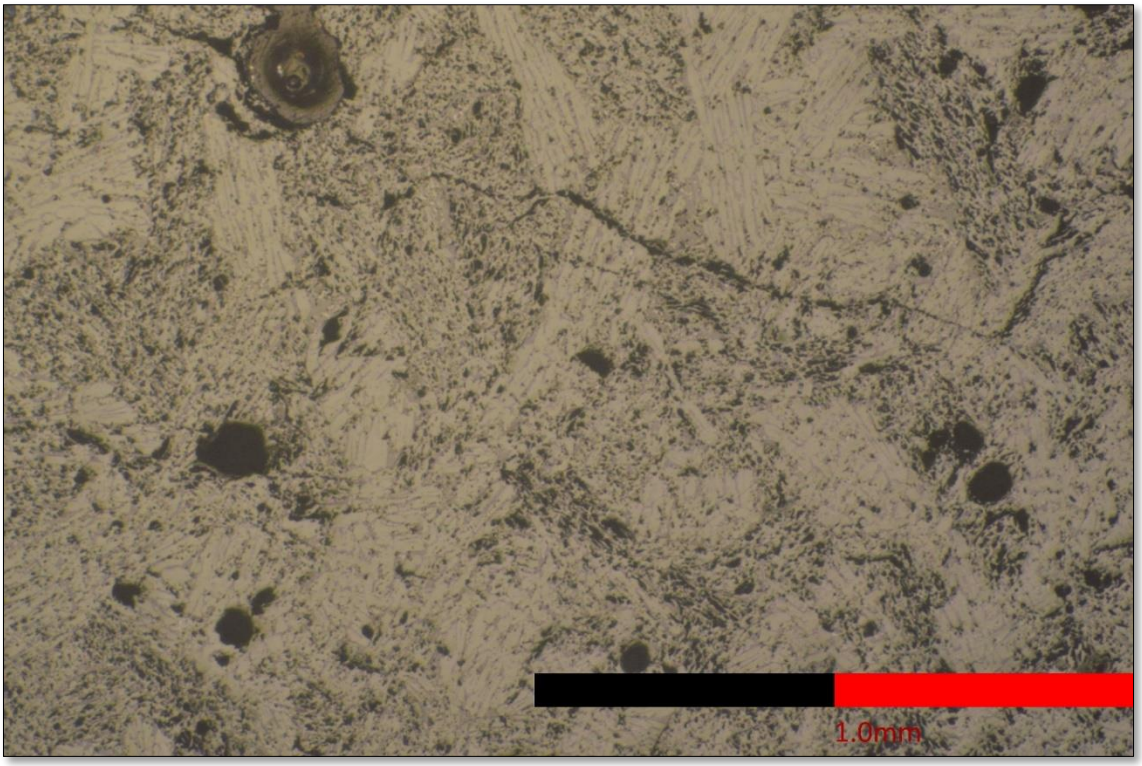

Plate 29, MGE 267 1 Fine fayalite laths

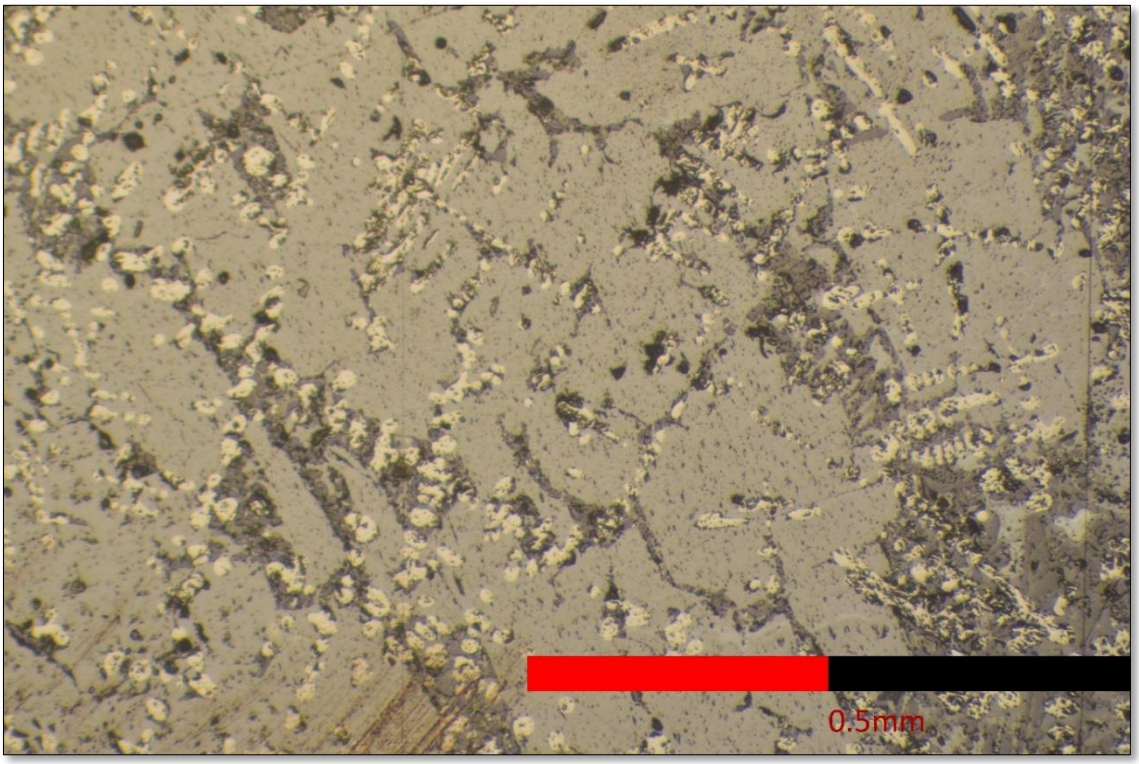

Plate 30, MGE 573 3, blocky fayalite, globular wüstite dendrites

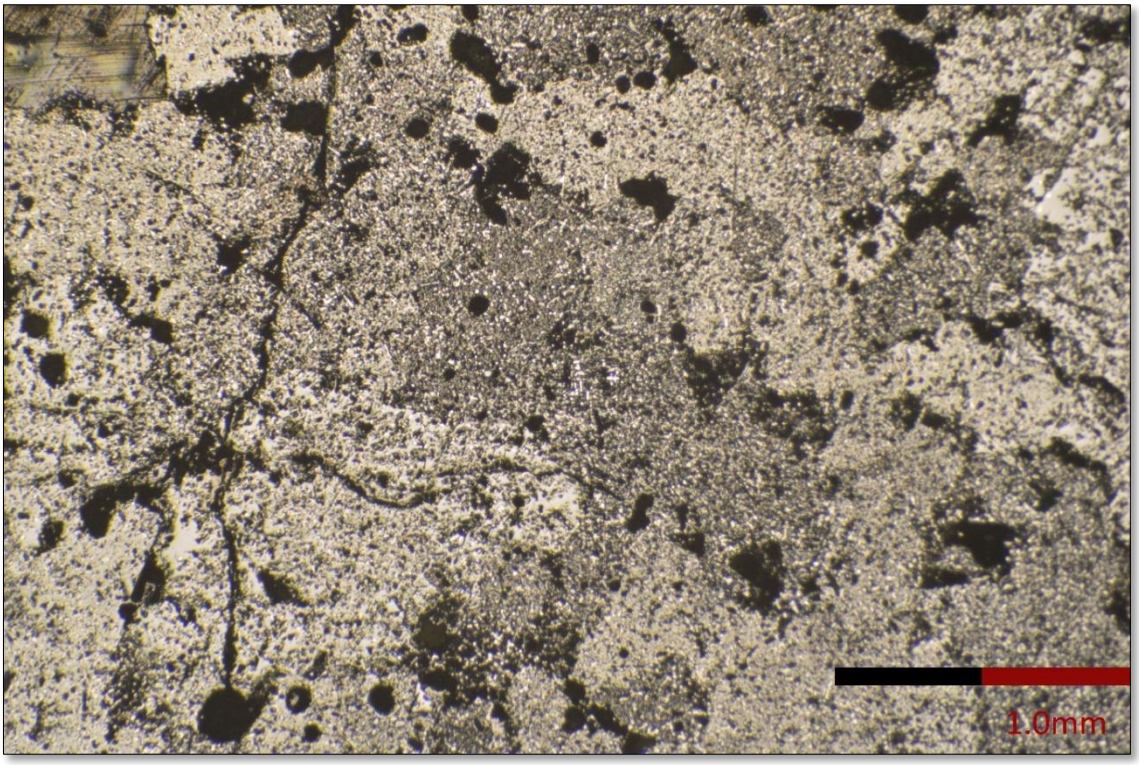

Plate 31, MGE 578 1, Blocky fayalite

'Life history'

The macro and micromorphology of the slag from this site suggests a furnace that was non-slag tapping was operating. The presence of sheets of more liquid slag is an indicator that the slag was very liquid at the point the furnace was opened. The furnace slag however was more viscous as shown by the level of trapped porosity. This together reveals that the slag was more liquid at the point it was opened to remove the bloom, as it would require changing the composition or increasing the temperature to change the liquidity this is something to examine using the chemical analysis.

Chemical composition

The slag from this site has high levels of iron oxide with one sample (MGE 578 1) very high (72% FeO). The silica levels of the slag are not elevated with MGE 578 1 having a silica amount towards the lower end of the normal range. The alumina levels are elevated but with low levels of calcium this suggests that this was a contribution from the clay of

the furnace lining rather than from the ore. The phosphorus levels are high suggesting that bog ore was being used this has the same implications for the metal product as with SES and GRR.

The liquidus temperature of these samples fall between 1150 and 1200°C mainly reflecting the variation in the iron oxide content. The viscosity of the slag is quite varied at low temperatures but mostly free flowing around 100°C above its liquidus temperature. The RII indicates that the smelting on this site was mostly less reducing, but one sample being more reducing shows variation in the reducing conditions, whether this was deliberate or accidental it is not possible to say.

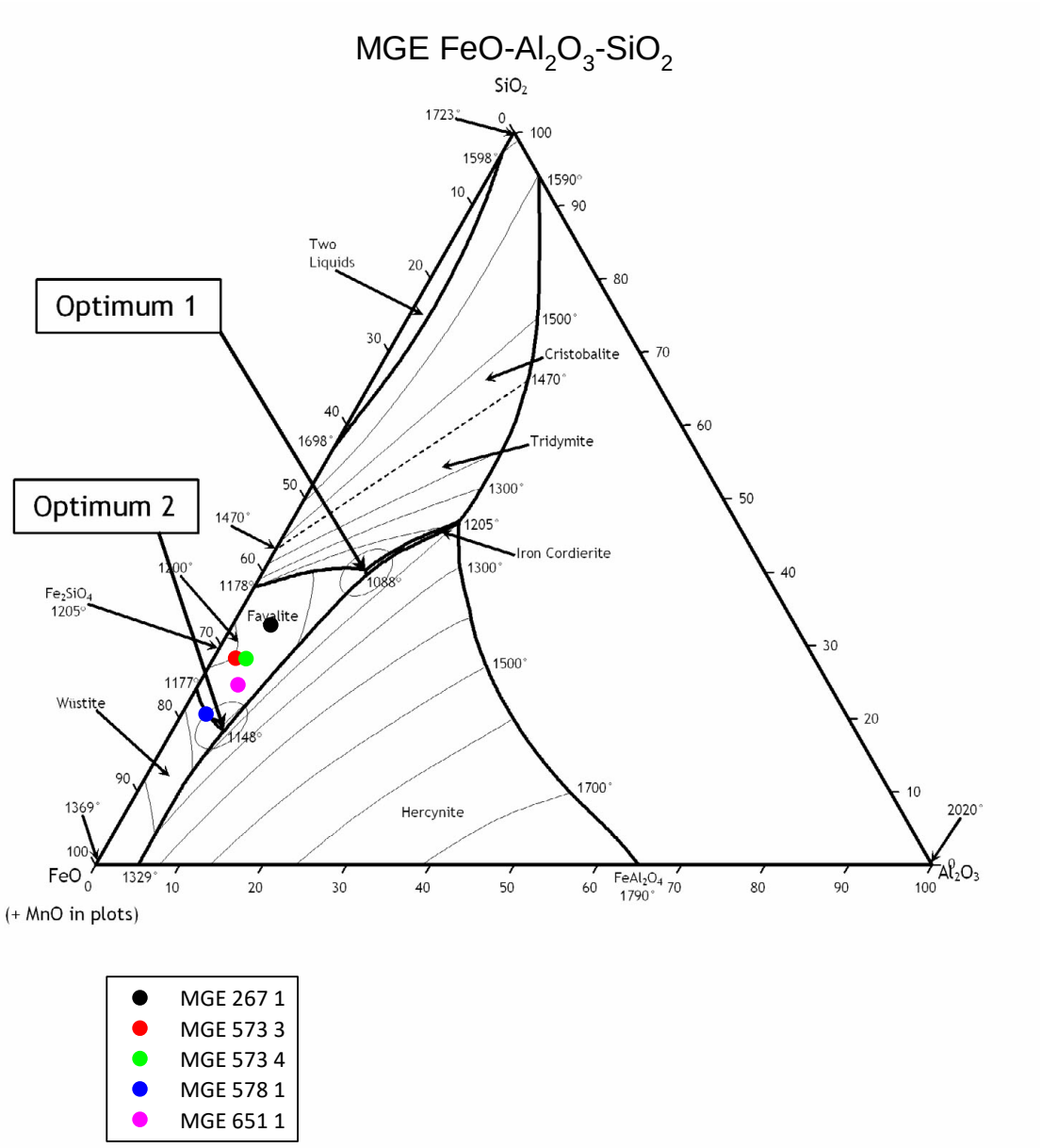

Figure 20, MGE FeO-Al2O3-SiO2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
MGE 267 1	0.5	0.4	4.5	30.2	2.3	1.6	1.4	0.3	0.8	58.5	100.5
MGE 573 3	0.5	1.0	2.6	25.2	3.4	1.4	2.5	b.d	0.4	63.2	100.3
MGE 573 4	0.4	0.4	4.0	26.4	1.7	0.8	0.9	b.d	0.5	65.3	100.4
MGE 578 1	b.d	b.d	3.0	18.9	3.6	0.2	1.7	b.d	0.4	72.6	100.3
MGE 651 1	0.7	b.d	4.5	21.7	5.9	0.6	2.3	b.d	0.5	64.0	100.2

Table 22, MGE composition

	1150°C	1200°C	1250°C	1300°C	1350°C
MGE 267 1	38.43	25.97	17.85	12.58	9.06
MGE 573 3	22.35	15.39	10.87	7.86	5.8
MGE 573 4	30.54	21.59	15.09	10.81	7.9
MGE 578 1	14.88	10.42	7.48	5.49	4.11
MGE 651 1	21.53	15.3	10.7	7.67	5.62

Table 23, MGE Viscosity (Poise)

	RII
MGE 267 1	1.22
MGE 573 3	0.95
MGE 573 4	0.96
MGE 578 1	0.62
MGE 651 1	0.80

Table 24, MGE RII (green – less reducing, red – more reducing)

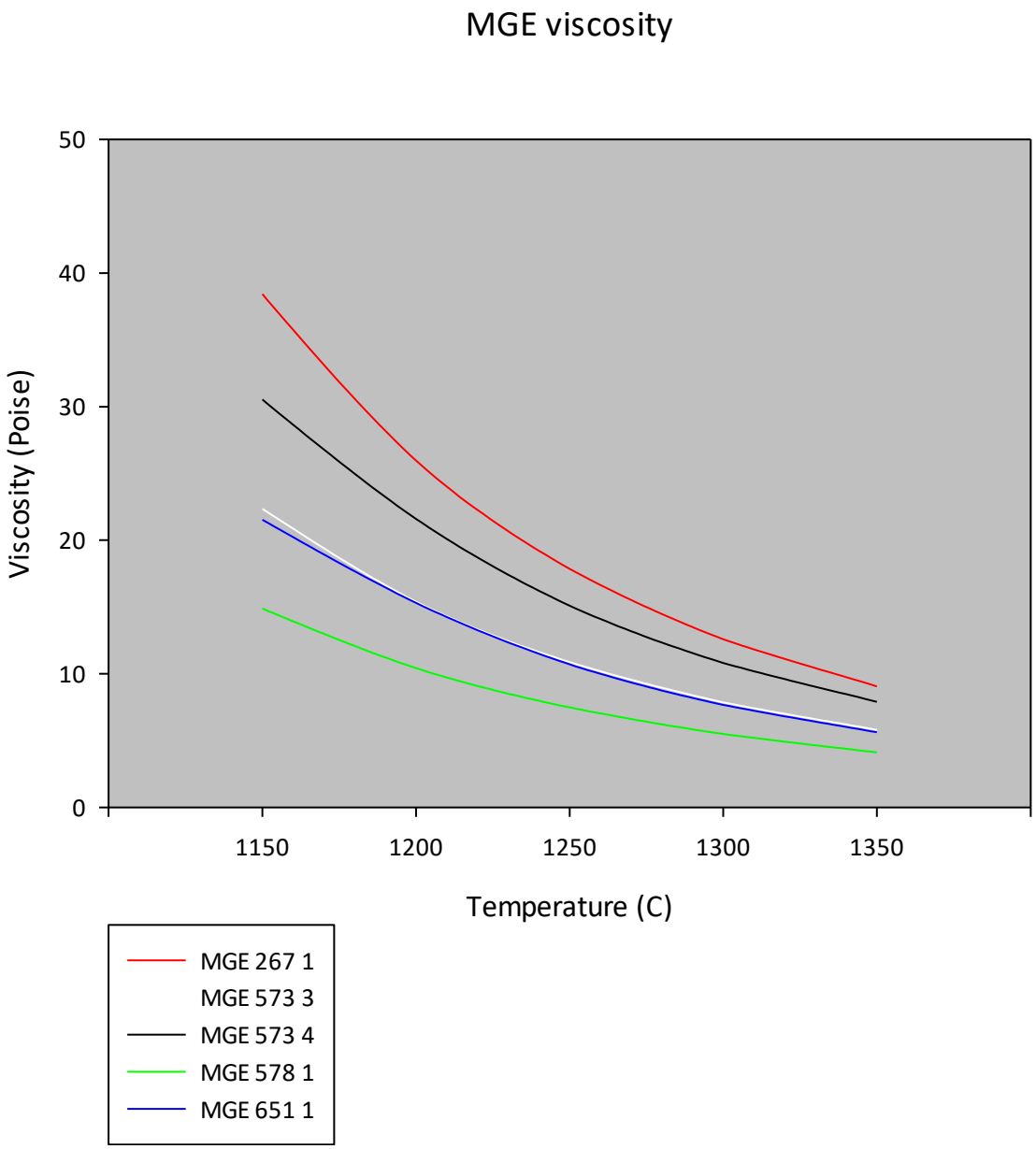

Figure 21, MGE Viscosity (Poise) vs Temperature (°C)

4.1.6 Shooter's Hill, London (SHH)

This slag was recovered from a ditch which the pottery assemblage has suggested to date from the 8th to 5th centuries BC. This has been suggested to be an enclosure ditch for a settlement but the scale of the excavation was very limited so it can only be suggested to be a small scale smelting event on a settlement site.

Macromorphology

The slag from this site was received having been already sampled, the macromorphological analysis of this slag will be taken from Dungworth and Mepham (2012). The slag recovered had a high density but most of the fragments are fairly small, weighing less than 100g. Most of these small fragments have been sufficiently fluid to have flowed to some degree, this material is generally irregular in shape. There are larger fragments (up to 1.2kg) which appear to be fragments of slag cakes. The morphology of the slag indicates it formed, flowed and solidified within the furnace (Dungworth and Mepham 2012). It is consistent to that found at Trevelgue head thought to be from a bowl furnace (Dungworth in Nowakowski 2011) or possibly a slag-pit furnace (Pleiner 2000, 149-63).

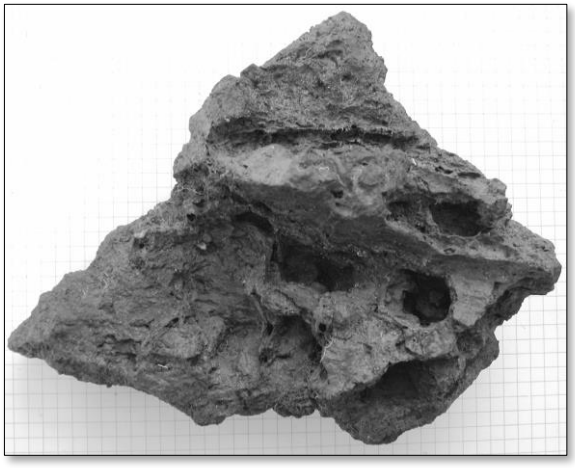

Plate 32, Cake/furnace slag (Dungworth and Mepham 2011)

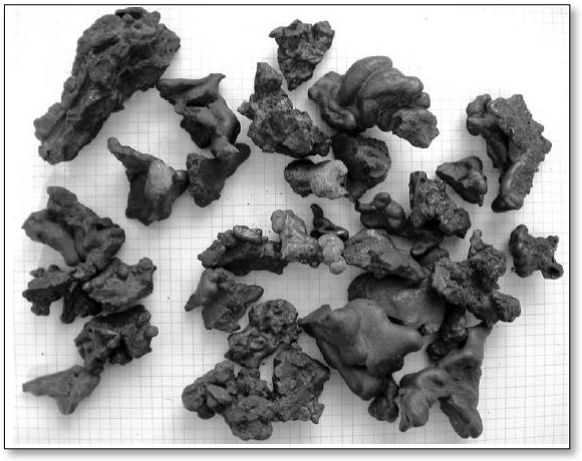

Plate 33, Slag runs/prills (Dungworth and Mepham 2011)

Micromorphology

The slag from this site is formed of three main phases, fayalite, wüstite and interstitial glass. Fayalite is present in blocky and blocky lath forms, both these suggest a slag which has cooled more slowly than rapidly. This would indicate slag which cooled over a long thermal gradient leading to the blockier form of fayalite. The wüstite varies between very frequent and moderately frequent, this would indicate a low to moderately reducing condition. This would lead to a reduced production of metal from the ore but it would suit a more liquid slag which would be beneficial for the separation of slag and metal. The presence of a moderate level of metallic prills indicates the iron was not fully incorporated into the bloom leading to small fragments remaining in the slag. These two pieces of evidence appear to be contradictory but it is possible that the full chemical composition of the slag will explain this.

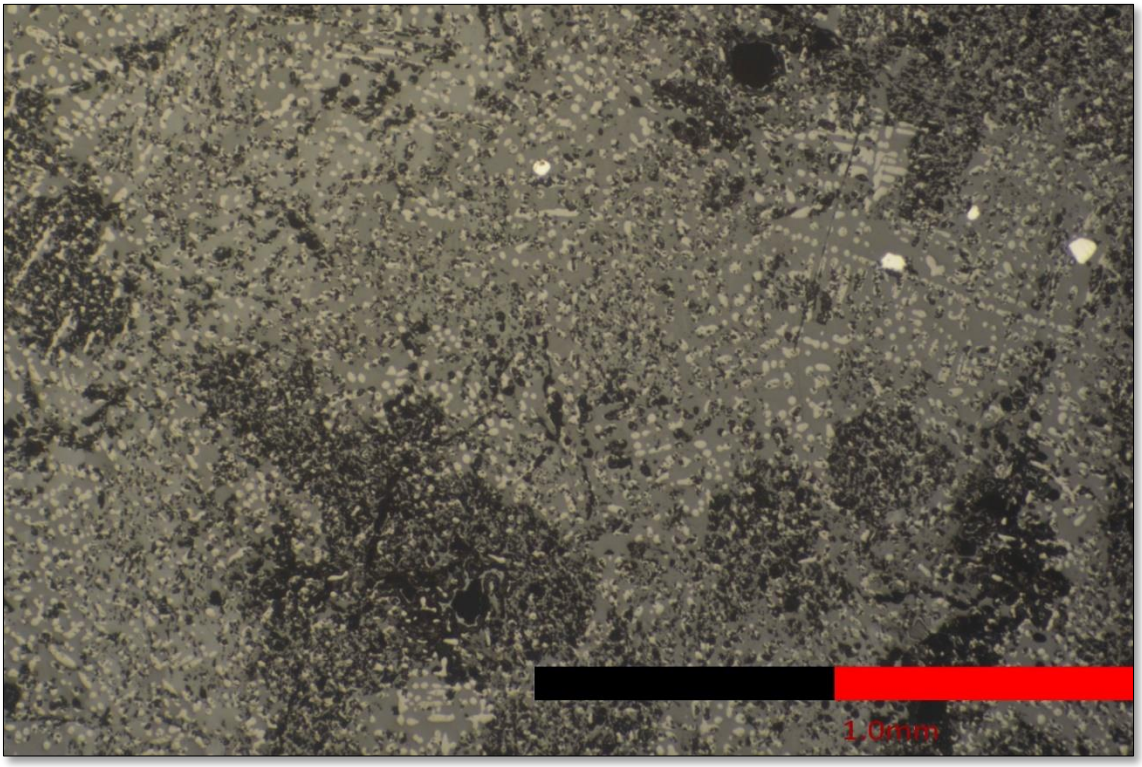

Plate 34, IW 040, metallic prills

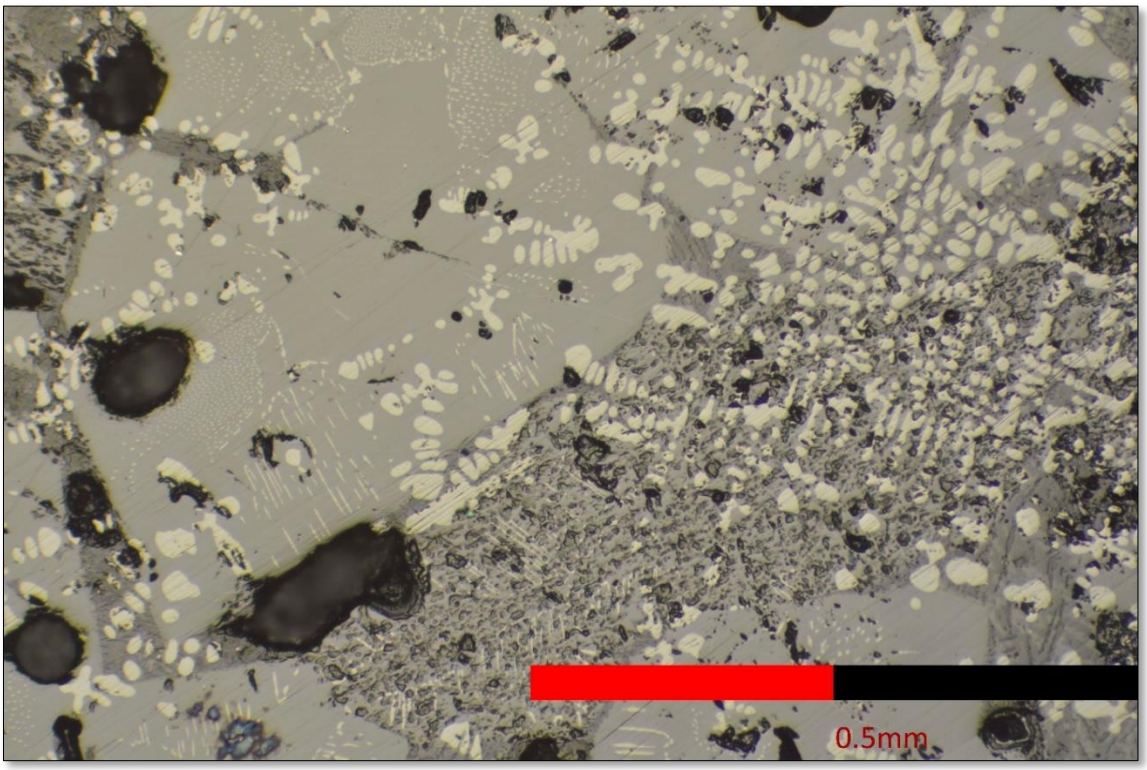

Plate 35, IW 041, blocky fayalite and globular wüstite dendrites

'Life history'

As the slag was received as pre-cut samples it is not possible to directly correlated macro and micro morphology. However the macromorphology report from this site describes the two main types which were samples as being prills and furnace slag. There are examples from the micromorphology which suggest that both of these types have been analysed. Where present the lath form of the silicate is blocky suggesting that even though the slag cooled at a moderate rate, these samples likely to have been prills that cooled within the base of the furnace. The blocky laths suggest that the temperature of the charcoal bed was quite high allowing the laths to grow in width creating a more blocky form. The presence of metallic prills suggests a slag that may have been too viscous for the metal to coalesce easily, the chemical composition will be used to calculate this along with the liquidus temperature.

Chemical composition

The samples from this site all have high levels of iron oxide, one of these (IW 032) is above the usual range of European bloomery smelting slag. All of the samples have a moderate amount of silica and a slightly elevated level of alumina. The calcium content is slightly elevated across all samples, the sample with the highest level of calcium corresponds to the sample with the lowest iron oxide content. This shows the calcium was able to flux the slag releasing more iron oxide to be reduced into metallic iron.

The liquidus temperature of the samples from this site are estimated to be between 1150°C and 1200°C. The variation in the iron content is giving all of the variation in the liquidus temperatures with higher iron oxide content resulting in a higher melting temperature. The viscosity of the slag would have been quite free flowing at a temperature close to its liquidus point. The RII of the samples from this site indicate that the smelt that produced it was less reducing.

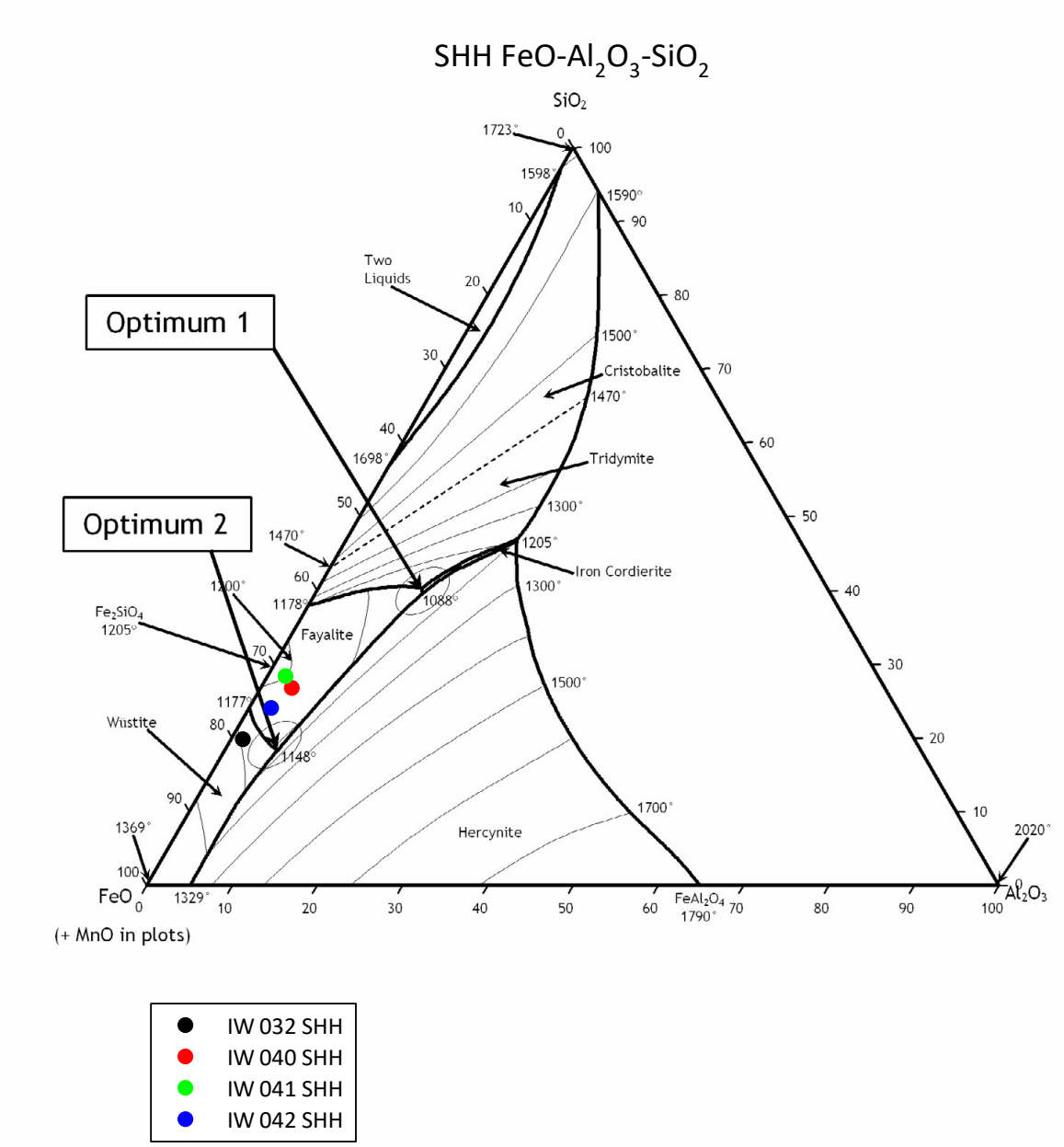

Figure 22, SHH FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
IW 032 SHH	0.7	0.6	2.1	18.5	0.7	0.3	2.6	b.d	0.3	74.6	100.5
IW 040 SHH	b.d	0.6	4.1	24.3	0.8	0.7	5.3	b.d	0.3	63.9	100.1
IW 041 SHH	b.d	0.4	2.7	26.3	1.9	0.5	3.2	b.d	b.d	65.3	100.2
IW 042 SHH	0.4	0.7	3.2	22.4	0.7	0.7	3.1	b.d	0.3	69.1	100.6

Table 25, SHH composition

	1150°C	1200°C	1250°C	1300°C	1350°C
IW 032 SHH	12.1	8.6	6.26	4.65	3.52
IW 040 SHH	18.58	12.78	9.02	6.52	4.81
IW 041 SHH	17.91	12.32	8.69	6.28	4.63
IW 042 SHH	25.45	17.76	12.71	9.3	6.94

Table 26, SHH Viscosity (Poise)

	RII
IW 032 SHH	0.59
IW 040 SHH	0.91
IW 041 SHH	0.96
IW 042 SHH	0.77

Table 27, SHH RII (Green – less reducing, Red – more reducing)

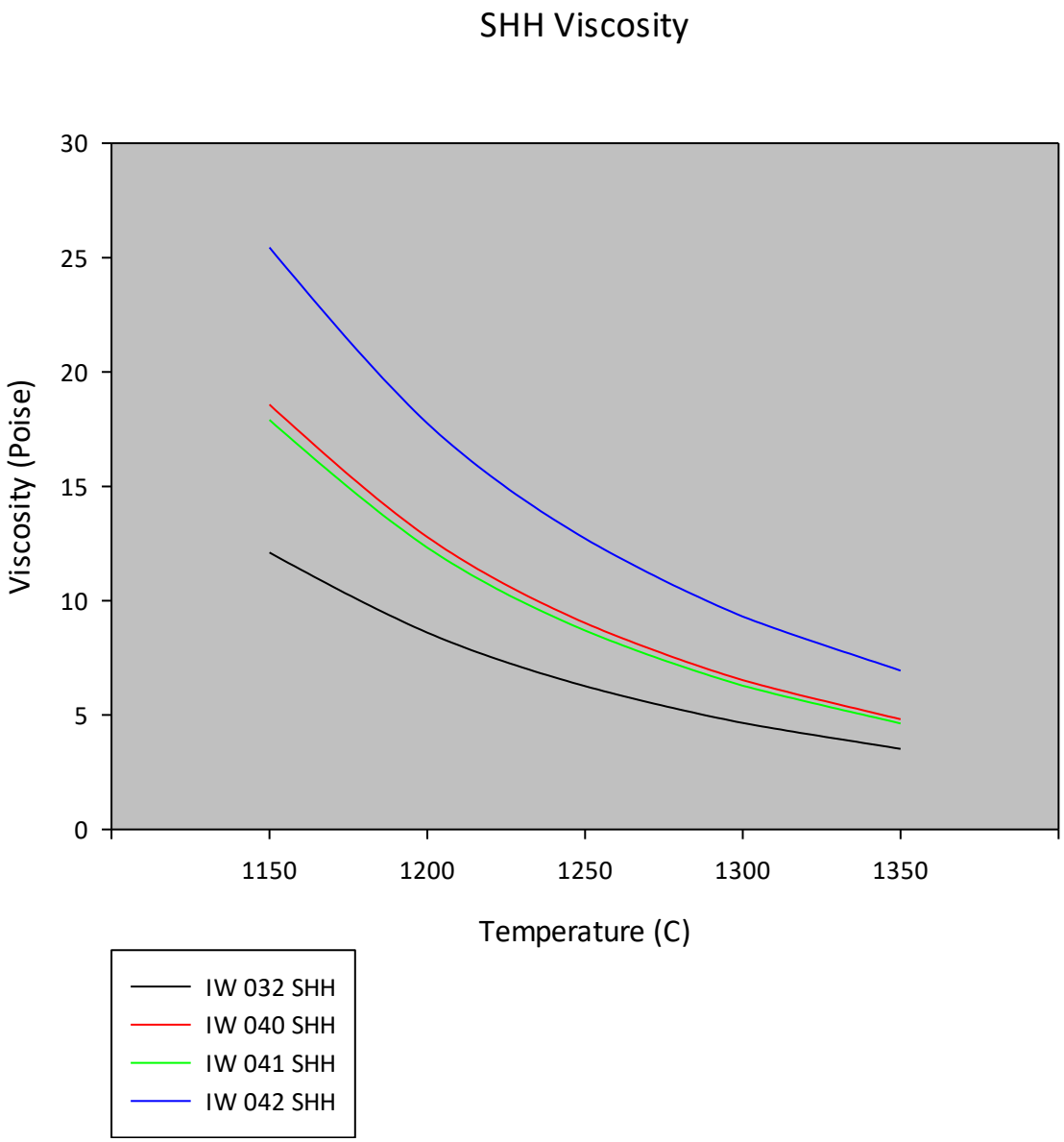

Figure 23, SHH Viscosity (Poise) vs Temperature (°C)

4.1.7 Lightwater, Camberley (LW)

The limited evidence suggests this was a large scale smelting site potentially reflecting several phases of iron smelting, with the final phases occurring in the late Iron Age.

Macromorphology

These samples were received having already been cut into small blocks, therefore macromorphological analysis is not possible.

Micromorphology

The slag from this site has a simple composition of three main phases, fayalite, wüstite and interstitial glass. The fayalite is present in a blocky to massive blocky form, this indicates it was held at a temperature which allowed the crystals to fully form. This indicates the slag was retained within the furnace during the smelt. The amount of wüstite present in the samples is either very high or very low or not present. This difference would either indicate a substantial difference in the reduction conditions during a single smelt or from different smelting events. The low level of free iron oxide indicates that there would have been more metal reduced from the ore and also potentially more carbon rich, steely iron. Many of the samples have a high level of glass which may indicate that there was a substantial contribution of alkali elements which mainly originate from the fuel ash and ore. The chemical analysis may show which of these contributed and what that would have meant for the smelt.

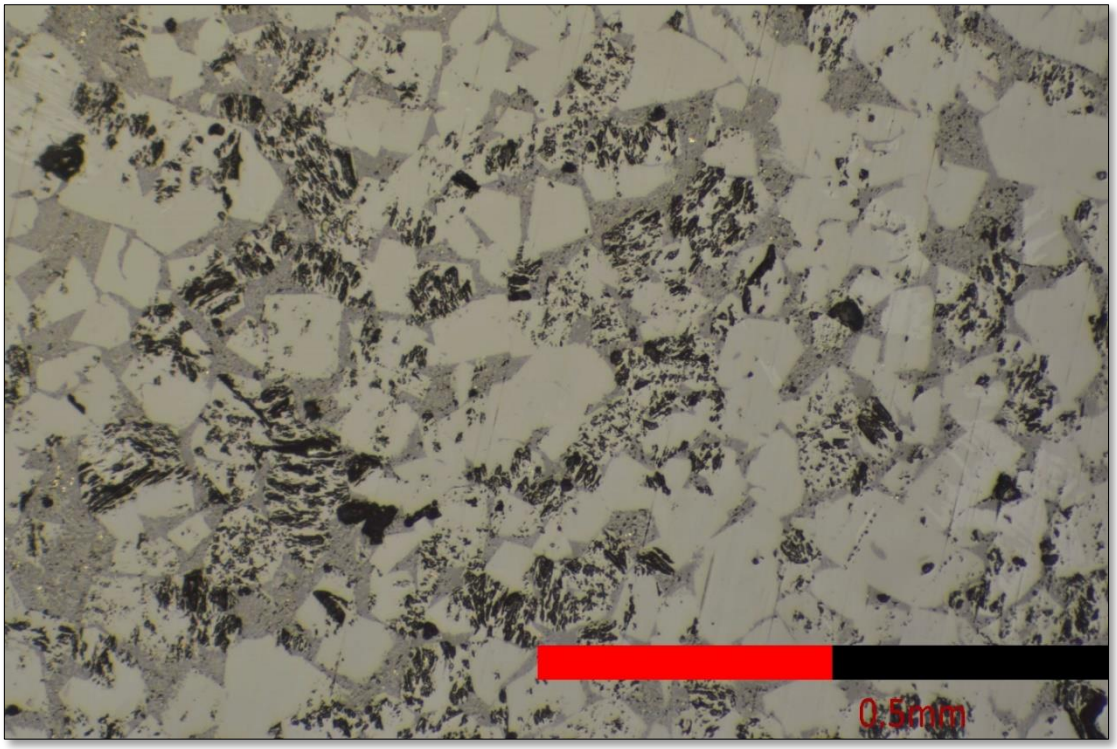

Plate 36, IW 035 blocky fayalite

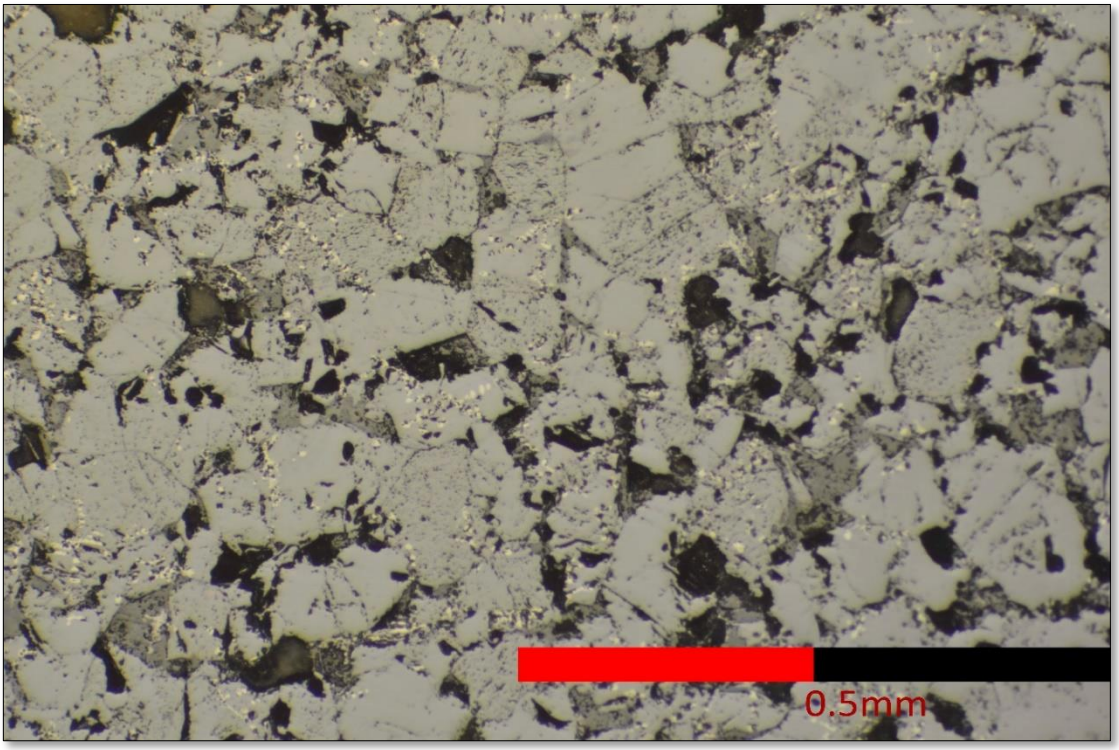

Plate 37, IW 038 blocky fayalite, low wüstite

'Life History'

The slag from this site was received as pre-cut blocks and the slag has not been described in detail in the site reports. Therefore the 'life history' of the slag has to be estimated from the microstructure alone. The microstructure has significant differences in the amount of free iron oxide present, whether this was a difference in the inputs to the process or the methods of the process will be examined using the chemical composition. The high proportion of glass in some of the samples may mean that there was a high level of alkali elements, these can have significant impact on the viscosity of the slag. Depending on which glass forming elements are present can reveal whether the ore or the fuel ash slag are contributing to the composition of the interstitial glass.

Chemical composition

The composition of the slag from this site has a high level of iron oxide with one (IW 055) above the typical range for European bloomery slag and one (IW 059) noticeably lower than the other samples. There is a high level of phosphorus present in all but one of the samples (IW 059). This indicates an ore with a high phosphorus content was being employed at this site and likely to have been bog ore (Paynter, 2006). The alumina is low to barely elevated in all but one sample (IW 059). The consistency of the phosphorus and relative consistency of the alumina content suggests all of the samples except IW 059 used the same source of ore.

The two samples; IW 055 and IW 059 which have the greatest difference in the iron oxide content are the most separate when the liquidus temperatures are calculated at 1250°C and 1150°C respectively. The remaining samples all plot close to the eutectic of fayalite. Apart from IW 059 all of the samples would have been free flowing by 1250°C. The RII of the samples

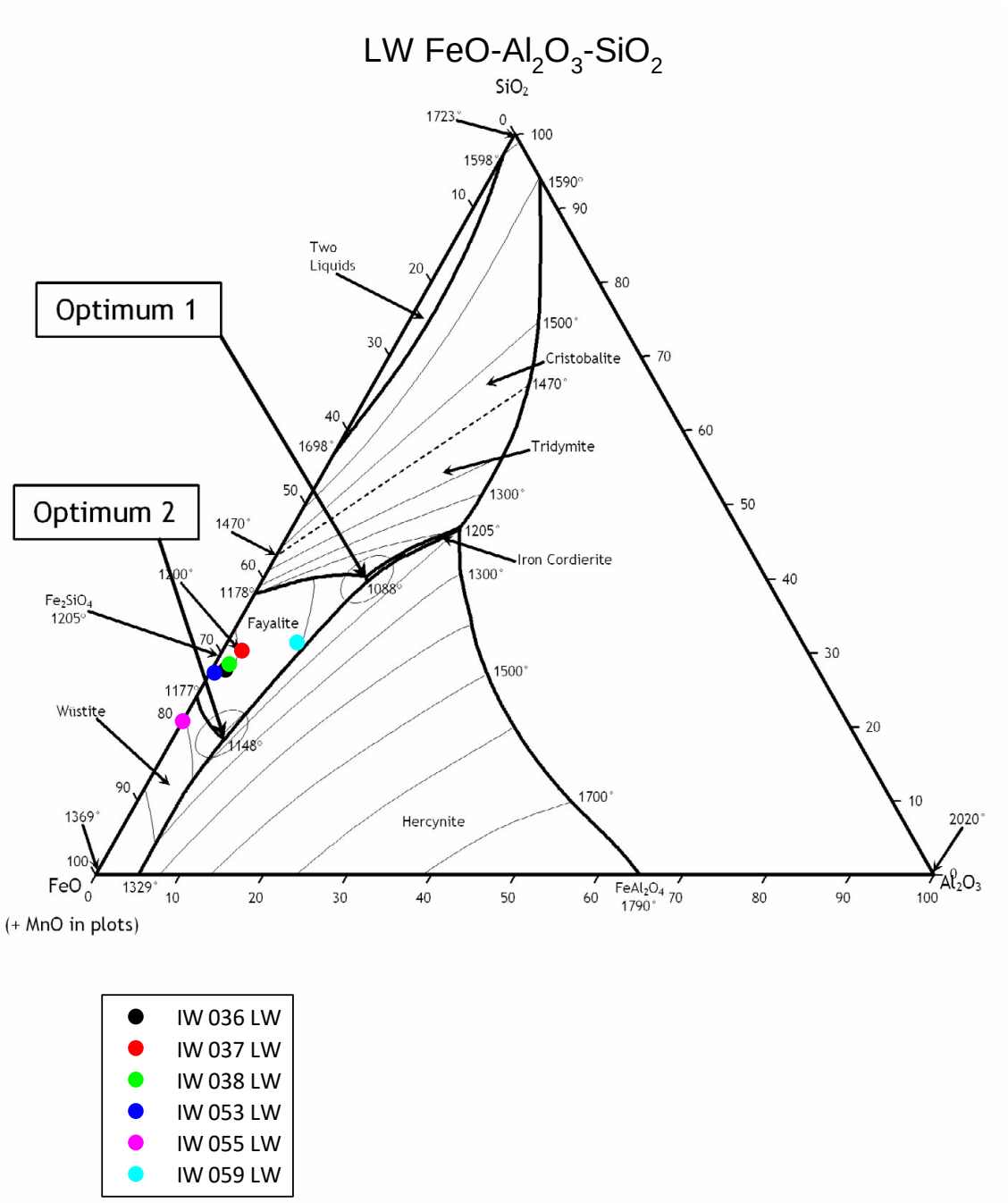

Figure 24, LW FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
IW 036 LW	0.9	0.4	1.8	25.3	7.2	0.7	1.8	b.d	2.8	61.5	102.5
IW 037 LW	b.d	0.5	2.4	27.7	5.5	1.1	1.6	b.d	1.0	60.5	100.3
IW 038 LW	b.d	0.5	1.9	26.2	5.8	0.2	1.9	b.d	1.4	62.6	100.4
IW 053 LW	b.d	b.d	0.8	25.3	5.4	0.4	1.6	b.d	0.7	66.0	100.2
IW 055 LW	b.d	0.3	0.4	19.5	4.8	0.3	1.0	b.d	0.4	73.8	100.4
IW 059 LW	b.d	1.3	7.9	28.7	0.9	2.2	4.3	b.d	0.6	54.4	100.4

Table 28, LW composition

	1150°C	1200°C	1250°C	1300°C	1350°C
IW 036 LW	30.63	21.09	14.9	10.77	7.95
IW 037 LW	28.63	19.48	13.61	9.74	7.12
IW 038 LW	26.42	18.14	12.78	9.21	6.79
IW 053 LW	18.44	12.81	9.12	6.65	4.94
IW 055 LW	13.43	9.54	6.94	5.16	3.91
IW 059 LW	45.28	29.85	20.25	14.09	10.04

Table 29, LW Viscosity (Poise)

	RII
IW 036 LW	0.94
IW 037 LW	1.08
IW 038 LW	0.98
IW 053 LW	0.91
IW 055 LW	0.63
IW 059 LW	1.25

Table 30, LW RII (green – less reducing, red – more reducing)

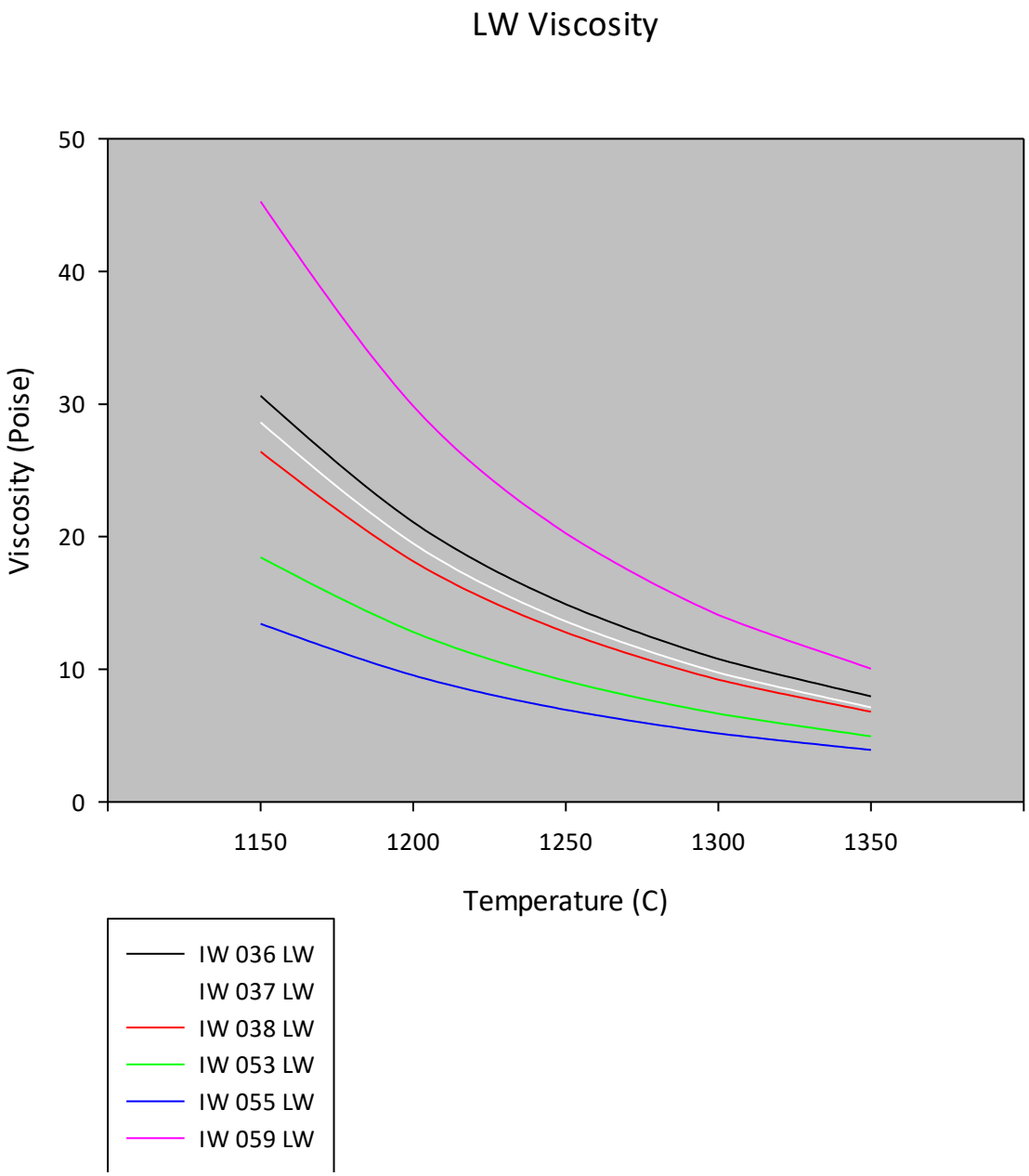

Figure 25, LW Viscosity (Poise) vs Temperature (°C)

4.1.8 All Canning's Cross (ACC)

This site represents a settlement site with associated smelting activity, this limited evidence suggests it was a small scale operation but with potential to be up to moderate sized.

Macromorphology

This assemblage has quite a large amount of variation but it is still dominated by slag formed within the furnace in one of two ways. There is some slag which is formed of a series of individual runs which have formed together. Despite similarities in the external appearance there are two different densities with some masses being dense and some having high porosity. The largest mass sampled has a roughly circular impression entering the mass horizontally in the upper portion. This is possible evidence for the interaction between the mass of slag and the air-race. This could be seen as the indicator of why the smelt was halted as enough slag accumulated enough to disrupt the airflow.

Plate 38, Impression caused by airflow into slag mass

The slag with higher porosity suggests that the slag was liquid for long enough for the dissolved gases to begin to form gaseous bubbles within the melt. The slag from this site had some mechanism for the collection of slag at the base of the furnace which led to the accumulation of the runs of slag. Some of the samples (plate 44) have evidence for this as masses with ropey flow marks on the upper surface and layering in cross section. While the surface has ropey flow marks the samples do not appear to have been tapped from the furnace, it is possible that further analysis may reveal greater detail.

Plate 39, Variation in macromorphology and multiple flow masses

Micromorphology

The microstructure of the slag from this site is characterised by a wide variation in the ratios and forms of the same main phases. Silicate in the form of fayalite and iron oxide in the form of wüstite with interstitial glass between these. The fayalite crystals are found in blocky and lath forms in different samples and even in the same sample. Where found in

the same sample this indicates that the sample cooled but over a moderate rate, it was not exposed outside the furnace environment nor was it held at a high enough temperature to allow full crystal growth. Where present the wüstite is present as globular dendrites. But interestingly there are samples with little or no free iron oxide in the form of wüstite.

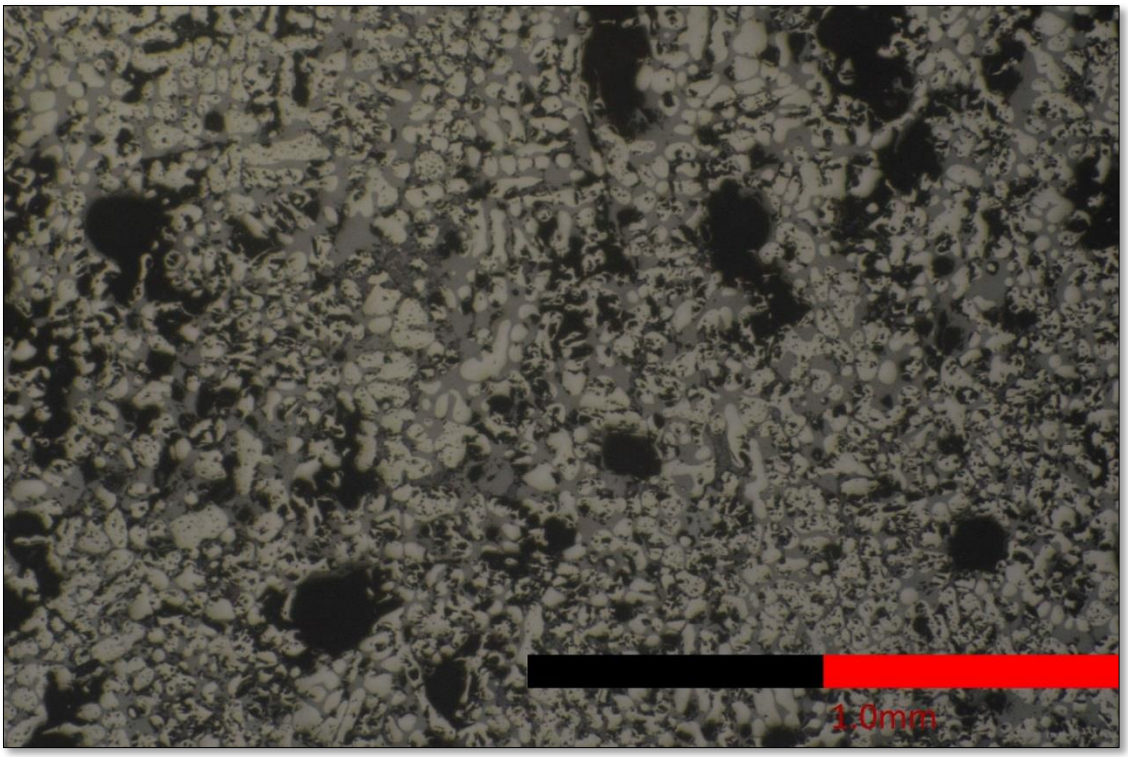

Plate 40, ACC 8 – high frequency of wüstite

There are halt lines of iron oxide in one of the samples where a layer of iron oxide enriched slag was formed. This was formed by the slag solidifying while the smelt was still in progress leading to a solid surface which further slag solidified upon. The structure of this iron oxide indicates it is magnetite which shows there was a short period at which the slag solidified where the reduction conditions became more oxidising, changing the wüstite to magnetite.

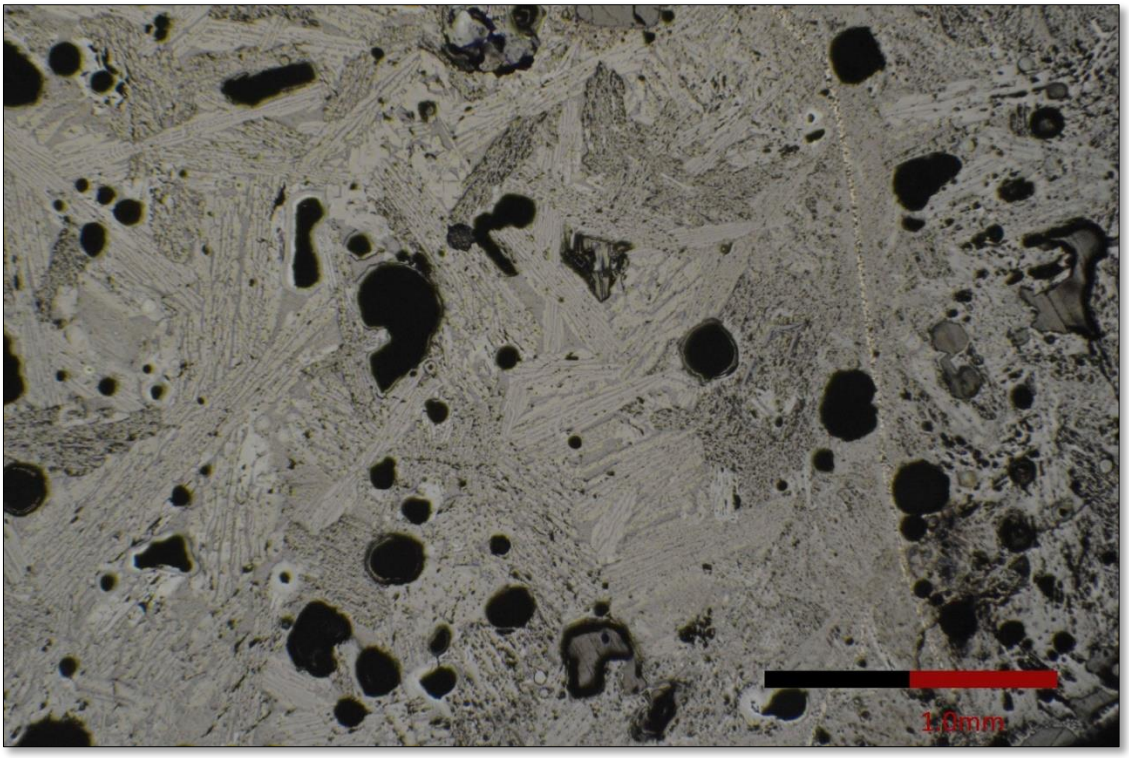

Plate 41, ACC 2 - fine fayalite laths and magnetite freeze line

Some of the samples have such a high level of wüstite that it obscures the rest of the microstructure of the slag. The variation of wüstite between the samples suggests that a range of carbon contents would have been produced from the furnaces on this site. The microstructures of the slag from this site suggest a high level of variability, confirming the evidence from the micromorphology.

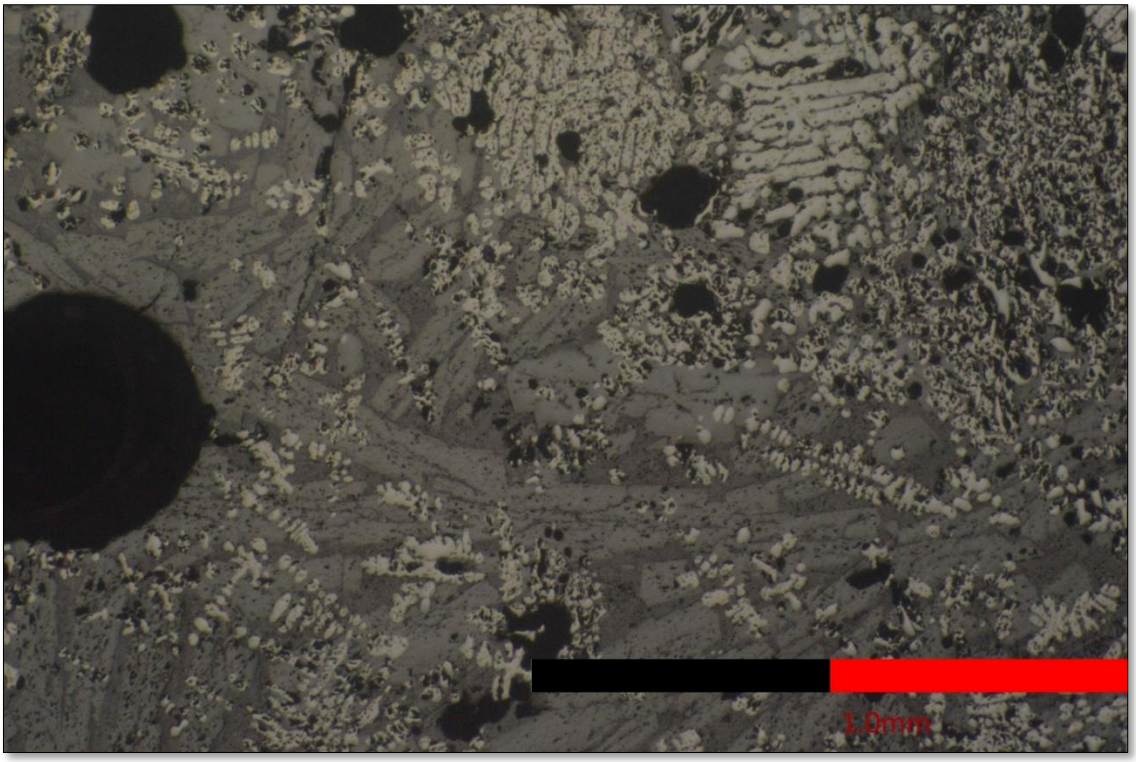

Plate 42, ACC 5 - variation in iron oxide content within a sample

'Life History'

The macro and micromorphology of the slag from this site shows a substantial variation within the assemblage but the indication is that the furnaces used on this site were all non slag tapping however the variation in macromorphology suggests furnaces with very different forms and operating procedures were used. The micromorphology also suggests this especially in the form and volume of iron oxide. To what extent these changes are the result of different inputs or different operation will be examined by the chemical analysis of the slag.

Chemical composition

The composition of the slag from this site shows variation within the silica, alumina and iron oxide composition. The variation in the other elements is quite limited suggesting a difference in process rather than raw materials. The amount of iron present is high and all

but one sample (ACC 8) are within the range of European bloomery slag (Pleiner 2000, 252). The alumina content ranges from low to very high but does not match with similar changes in the calcium content indicating this is a variation caused by different amounts of furnace lining becoming incorporated into the slag. The variation in the ratio between the silica and iron oxide content is a reflection of changes in the reduction conditions in the furnace.

The estimated liquidus temperature varies substantially in conjunction with the amount of iron oxide, with the higher iron oxide content generally relating to a higher melting temperature, however in conjunction with a higher alumina content the liquidus can be reduced. The liquidus temperatures range from 1150°C to 1250°C. The viscosity of the samples are quite varied as suggested by the range of compositions, ACC 1 in particular would have been very viscous at all temperatures possible in a bloomery furnace. Sample ACC 7 would have been free flowing at 1300°C all other samples would have been free flowing at 1250°C. The RII of the samples shows that the control over the reduction conditions was poor, with sample ACC 8 having a very poorly reducing environment and ACC 1 having a very reducing atmosphere.

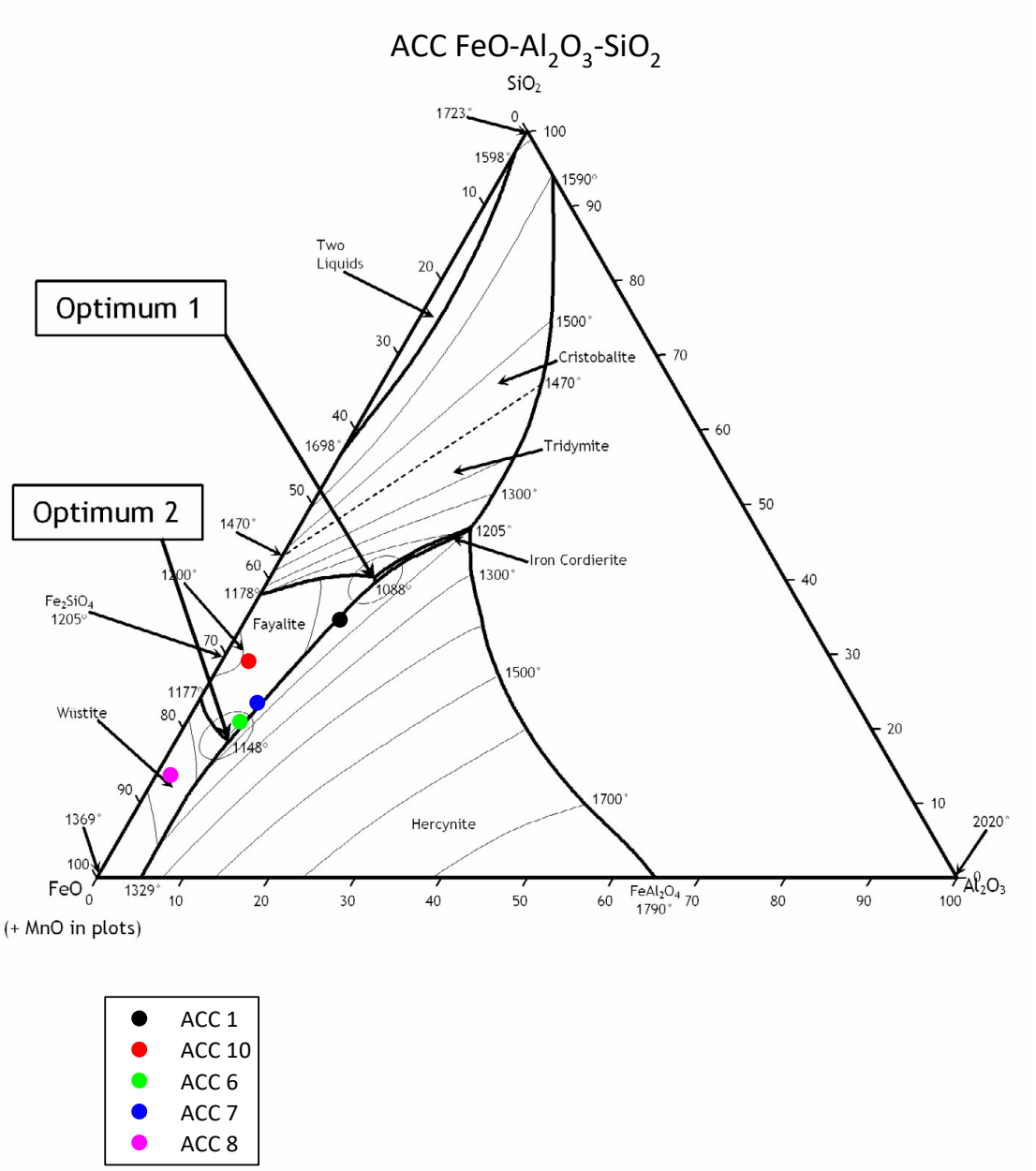

Figure 26, ACC FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
ACC 1	1.0	0.9	10.7	32.7	1.1	2.8	1.3	b.d	0.9	50.7	102.1
ACC 10	b.d	0.8	3.3	28.0	b.d	1.3	1.6	b.d	b.d	65.8	100.8
ACC 6	b.d	0.9	6.4	20.3	1.4	0.8	0.6	0.7	0.7	70.5	102.2
ACC 7	b.d	0.7	7.0	22.6	1.2	0.8	0.6	0.5	0.7	66.7	100.9
ACC 8	0.5	0.9	1.9	13.2	0.4	0.8	1.4	b.d	0.4	81.5	101.1

Table 31, ACC composition

	1150°C	1200°C	1250°C	1300°C	1350°C
ACC 1	101.02	64.05	41.9	28.19	19.46
ACC 10	24.85	16.96	11.9	8.55	6.28
ACC 6	38.3	26.30	18.53	13.36	9.84
ACC 7	44.37	30.59	21.28	15.16	11.04
ACC 8	9.34	6.8	5.06	3.8	2.96

Table 32, ACC Viscosity (Poise)

	RII
ACC 1	1.51
ACC 10	1.02
ACC 6	0.68
ACC 7	0.80
ACC 8	0.39

Table 33, ACC RII (green less reducing, red more reducing)

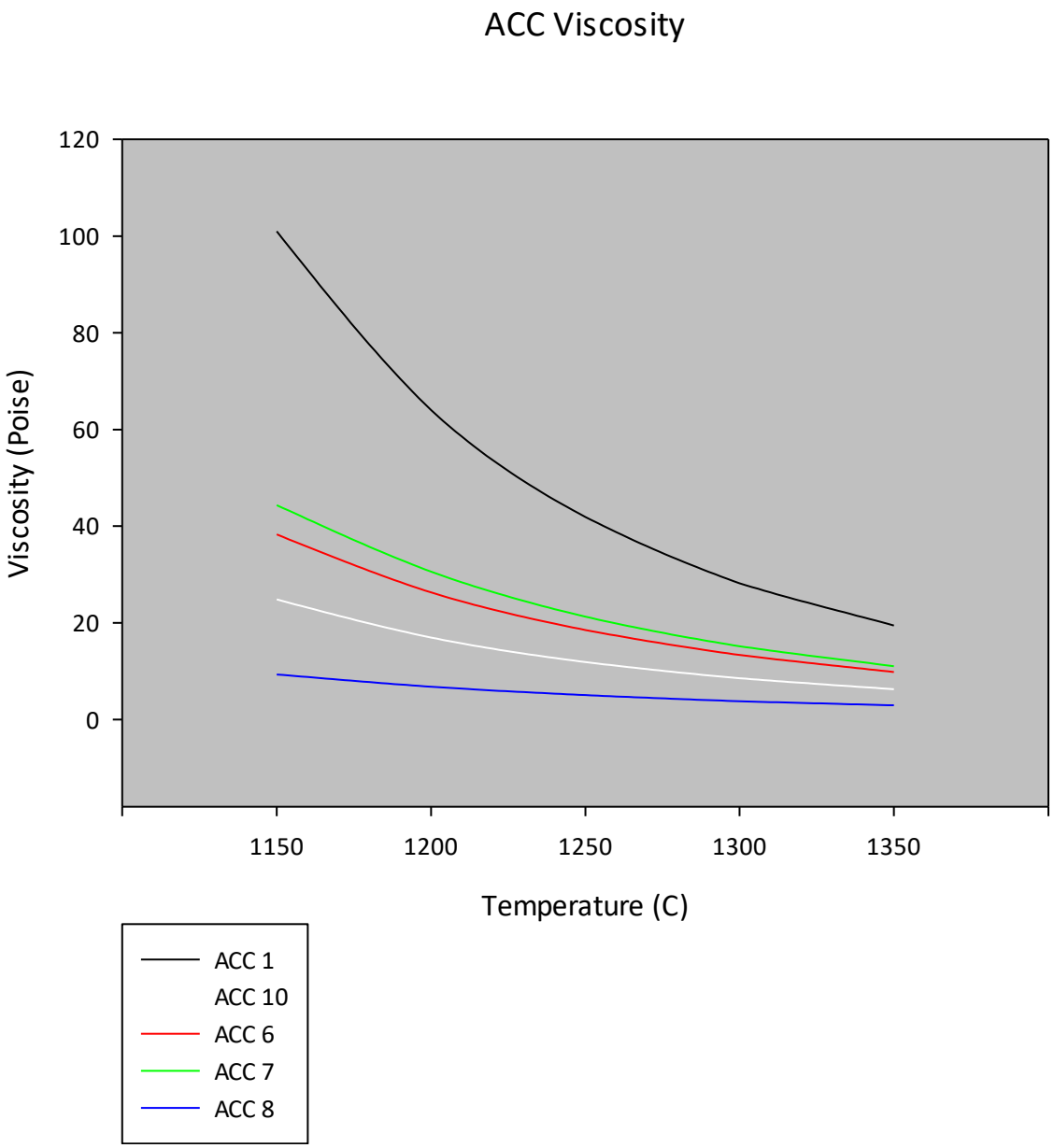

Figure 27, ACC Viscosity (Poise) vs Temperature (°C)

4.2 TRANSITIONAL SITES

4.2.1 Rose Cottage, Dymock (RCD)

Slag was found across this site in features dating to the 2nd century, despite the assemblage of slag recovered there was no evidence for furnaces. It is one of a series of sites in the immediate vicinity which have evidence for iron smelting and other metalworking.

Macromorphology

The available assemblage from this site is dominated by slag associated with slag tapping. Tap slag with characteristic ropey flow marks and smooth underside was found across this site.

Plate 43, 'Typical' tap slag

Also recovered were a number of slag tubes, these include stacks of tubes. The slag tubes have different diameters suggesting they are not from the same furnace. The stacks of tubes are not consistent with the theory that slag tubes were formed by the removal of bellows and slag flowing into an open tuyere. They appear to fit with the theory that a hole was opened into the furnace to drain slag. There are other features of some of the tubes which support this theory. There are two tubes which have angled funnel shaped ends leading to

full diameter tubes. The assemblage deposited with the museum is not representative of a complete assemblage. Slag tubes are overrepresented in this assemblage compared to other types of slag.

Plate 44, Narrow slag tube

Plate 45, Broad slag tube with 'funnel' end

Micromorphology

The samples from this site are dominated by high levels of iron oxide in the form of wüstite dendrites. The iron silicate in these samples is universally in the lath form. Metallic prills are also very common across the assemblage, they are in either globular or irregular 'splat' forms.

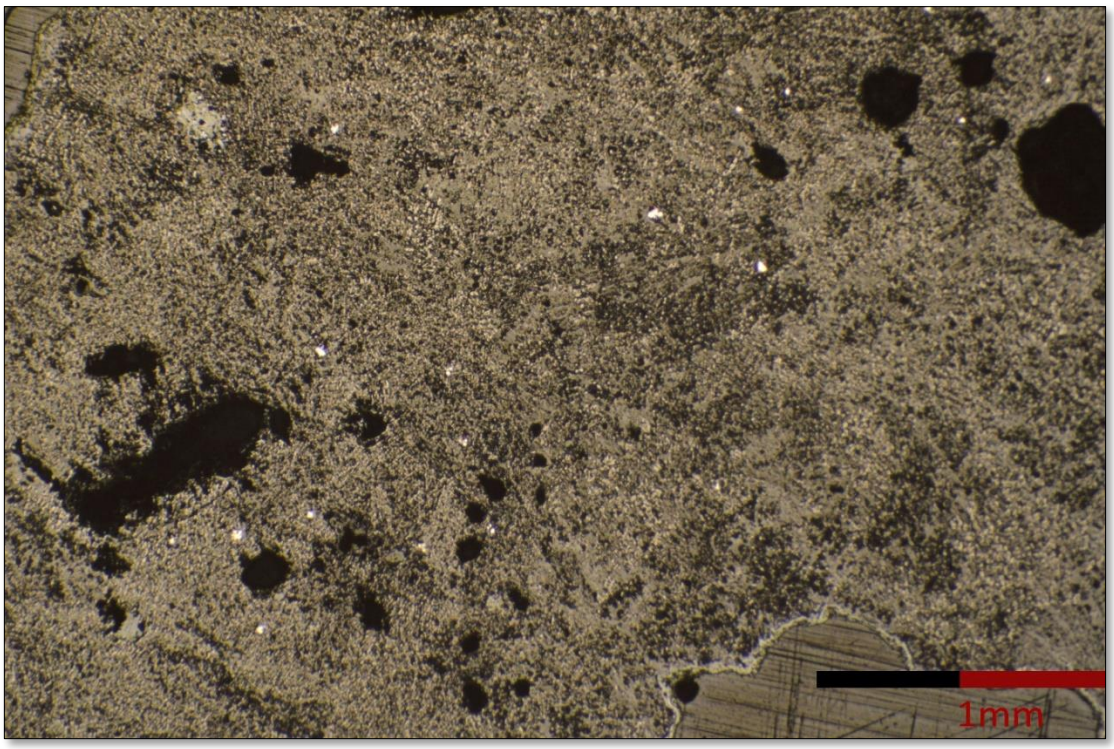

Plate 46, RCD 15 2, metallic prills in globular and 'splat' form

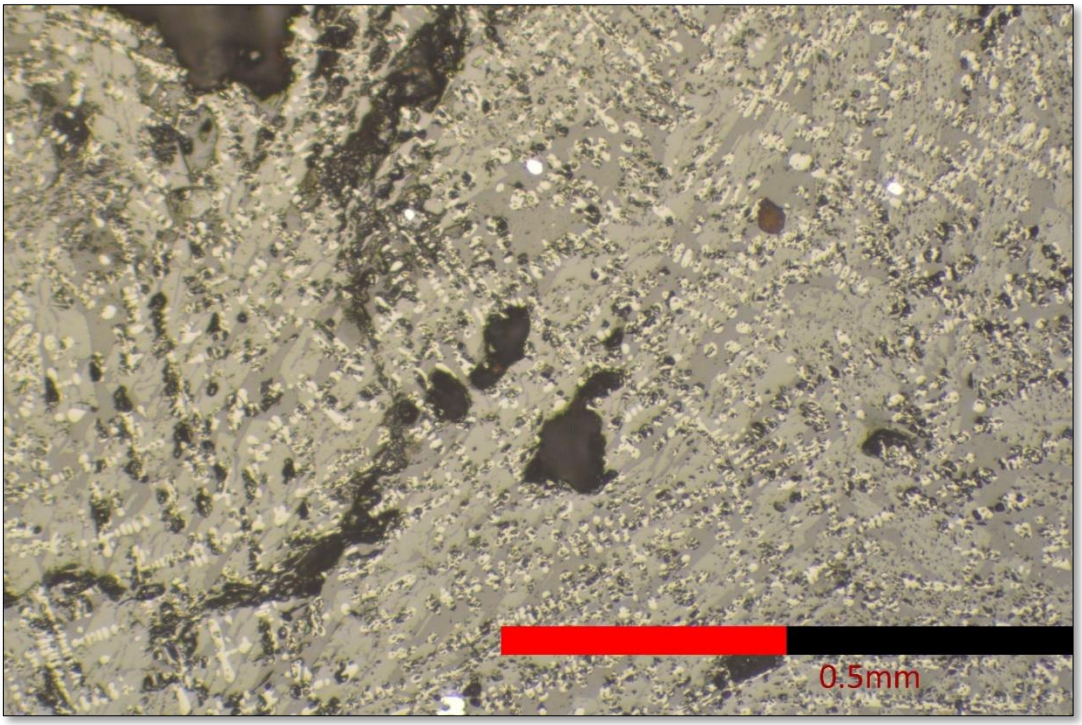

Plate 47, RCD 15 4, metallic prills and lath fayalite

The high levels of iron oxide present in these samples suggest an inefficient reduction process, but could have created a free flowing slag at close to its liquidus temperature. The fine silicate laths indicate the slag cooled over a short thermal gradient over a short period. The frequent metallic prills suggest that the properties of the slag were hampering the formation of the bloom.

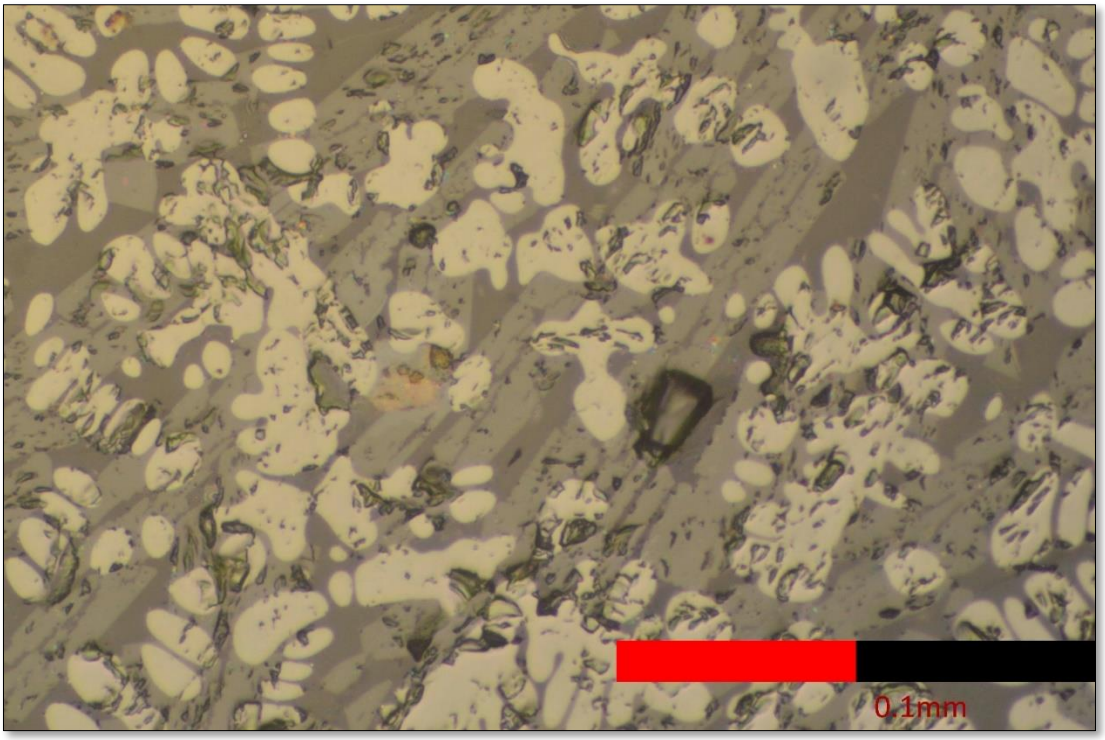

Plate 48, RCD 37 2, lath fayalite

'Life History'

The macro and micro morphological results of the slag from this site combine to indicate that a slag tapping furnace was being used at this site. The difference between the tube and tap slag from this site which have very similar micromorphologies will be studied using the chemical analysis to examine the liquidus and viscosities of these different types of slag. The presence of high numbers of metallic prills in some of the samples suggest that something stopped all of the metal forming a bloom. The viscosity of the slag will be important to understand why not all of the metal was collected into the bloom. The stacks of tubes should represent different periods of the smelt therefore studying the chemical composition would show the variation within the smelt.

Chemical composition

The slag from this site has a high iron content within the range expected for European bloomery smelting slag. The calcium level in the slag is slightly elevated as is the alumina

this suggests these are related and a result of the ore used. The low level of phosphorus suggests that this was not coming from the ore, this would produce a non-phosphoric iron. Without the phosphorus becoming incorporated in the iron lattice it is possible to produce metal which can include carbon.

The liquidus temperature estimated using the Al_2O_3-SiO_2-FeO phase diagram shows the melting temperatures were between 1150°C and 1175°C. The elevated alumina and iron oxide levels push these samples towards Rehren *et al.*'s optimum 2 (Rehren *et al.* 2007). All of the slag would have been free flowing at 1250°C. The RII from these samples shows that the furnace was less rather than more reducing, the two samples which show more reducing conditions are very close to 1.0 indicting they were only slightly increased in reducing gases.

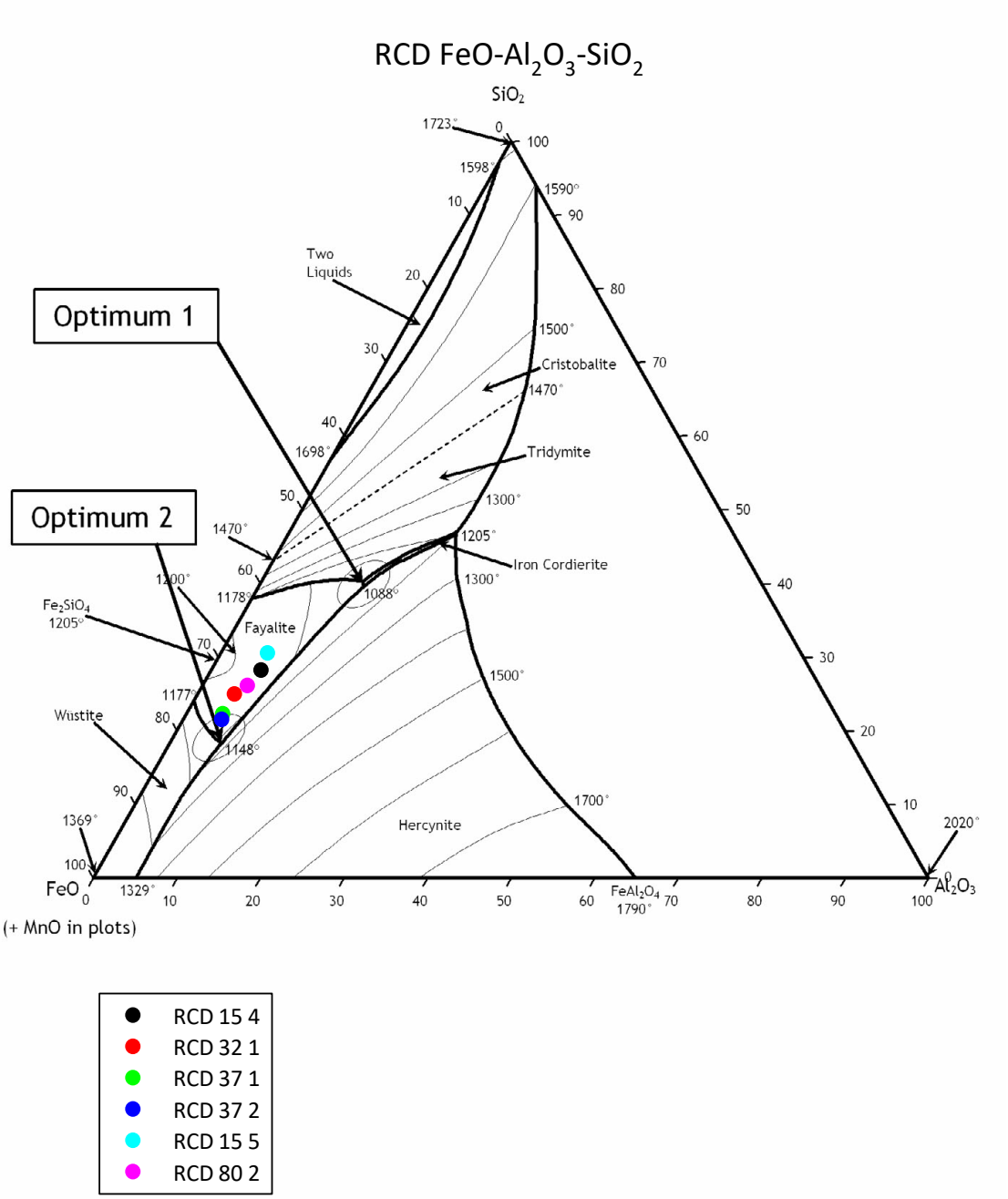

Figure 28, RCD FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
RCD 15 4	0.4	1.1	6.1	25.7	0.6	1.9	3.8	0.3	0.3	60.5	100.7
RCD 32 1	0.5	1.0	4.6	22.4	0.7	1.9	4.7	b.d	b.d	64.4	100.3
RCD 37 1	0.6	1.0	4.7	20.7	0.6	1.3	2.6	0.3	0.4	69.0	101.1
RCD 37 2	0.3	0.9	4.9	20.0	0.6	1.3	2.2	0.3	0.3	69.6	100.4
RCD 15 5	0.6	1.2	5.6	27.5	0.7	2.3	4.3	0.4	0.4	57.8	100.7
RCD 80 2	0.7	1.1	5.6	23.9	b.d	2.0	3.7	b.d	b.d	63.6	100.6

Table 34, RCD composition

	1150°C	1200°C	1250°C	1300°C	1350°C
RCD 15 4	28.86	19.14	13.28	9.43	6.85
RCD 32 1	18.63	12.85	9.09	6.58	4.87
RCD 37 1	19.73	13.68	9.73	7.08	5.26
RCD 37 2	18.05	13.97	9.94	7.23	5.37
RCD 15 5	29.56	19.91	13.78	9.77	7.09
RCD 80 2	23.53	15.95	11.18	8.03	5.89

Table 35, RCD Viscosity (Poise)

	RII
RCD 15 4	1.01
RCD 32 1	0.83
RCD 37 1	0.71
RCD 37 2	0.68
RCD 15 5	1.13
RCD 80 2	0.90

Table 36, RCD RII (green – less reducing, red – more reducing)

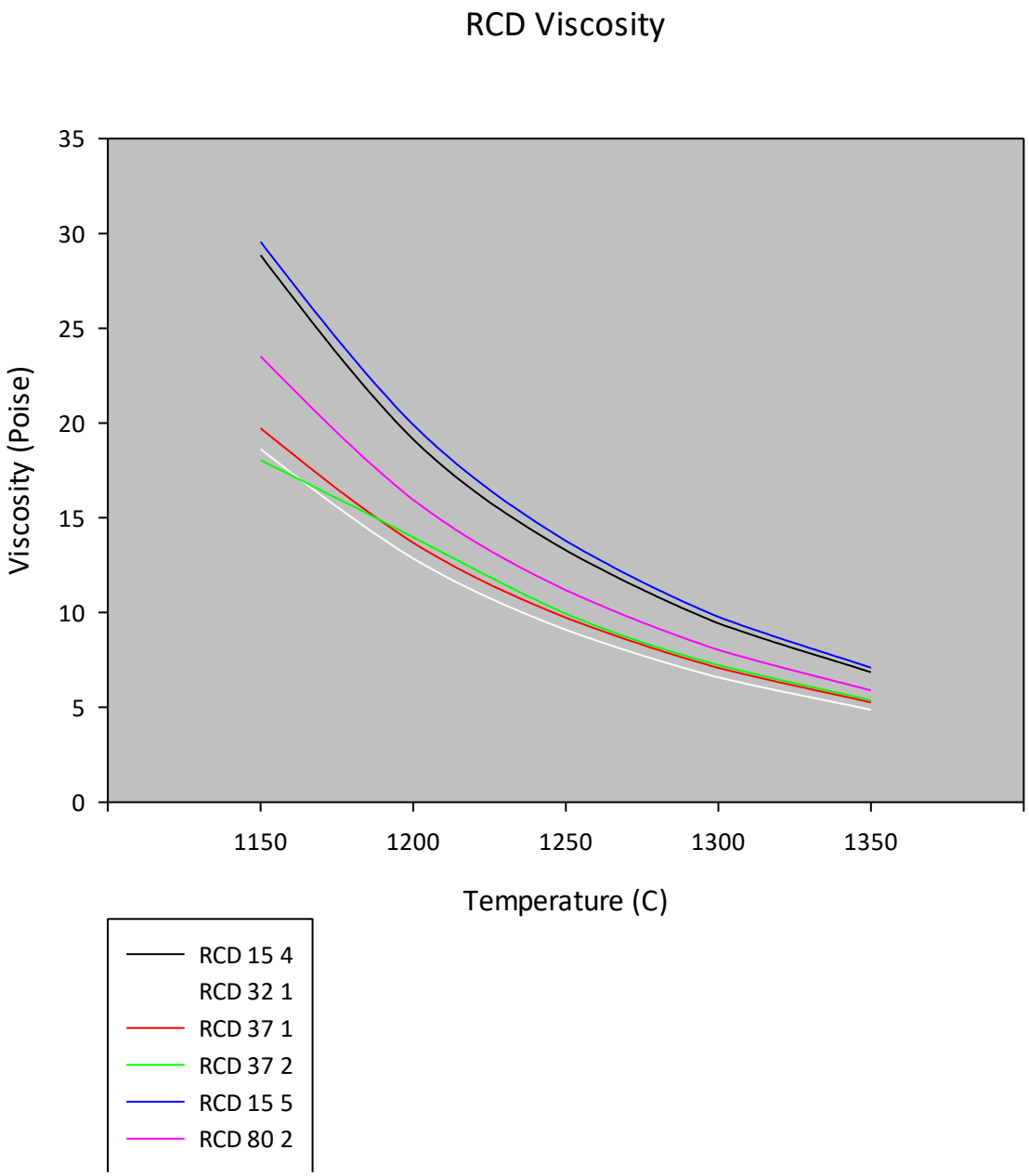

Figure 29, RCD Viscosity (Poise) vs Temperature (°C)

4.2.2 Dymock Sewage Works, Dymock (DSW)

The slag from this site was recovered from features dating from 120 AD to 150 AD. This site is part of the wider settlement of Dymock which is likely to have been a specialised metalworking roadside settlement.

Macromorphology

The available assemblage from this site is dominated by slag associated with slag tapping. Tap slag with characteristic ropey flow marks and a smooth underside was found across this site. There are two types of tap slag from this site, firstly dense slag with few but large voids, these solidified quite quickly not allowing for gases to precipitate out of the slag, the second type has much more frequent and smaller gas bubbles caused by being liquid for longer allowing for the gas dissolved in the slag to form bubbles. Individual slag tubes were recovered which have very different dimensions. These differences in size would indicate that the slag flowed into different sized voids. One of these is significantly too large to have been formed by slag flowing into a tuyere. It is roughly oval in shape, measuring 30mm high by 40mm wide with a funnel shape at one end which is wider and is 300mm long. This shows the width of the furnace wall at the point the slag flowed through it was around 300mm.

Plate 49, Slag tube

Plate 50, Dense tap slag

Micromorphology

The samples from this site are dominated by fine silicate laths and frequent to very frequent skeletal wüstite dendrites. Some of the samples are formed of multiple runs of slag, at the boundaries of these there is a concentration of iron oxide in the form of magnetite. There is a moderate amount of metallic prills through many of the samples.

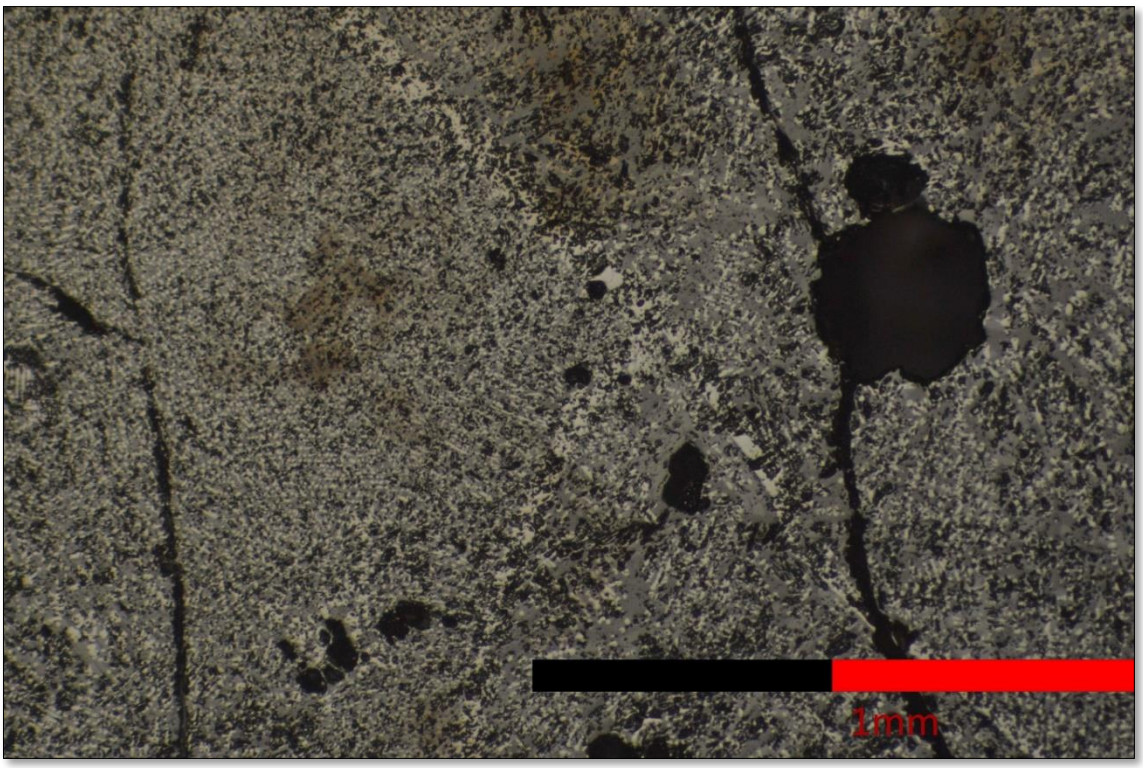

Plate 51, DSW 1067 1, magnetite freeze lines

The fine silicate laths in these samples indicates the slag was cooled rapidly over a short thermal gradient, which is supported by the skeletal tightly formed structure of much of the wüstite. The moderate to high levels of free iron oxide shows that the process which formed this slag was not particularly efficient at reducing iron oxide from the ore to metallic iron. This amount of free iron oxide in the slag would suggest it was free flowing close to its liquidus temperature and therefore the furnace would not need to be operated at a temperature significantly beyond this.

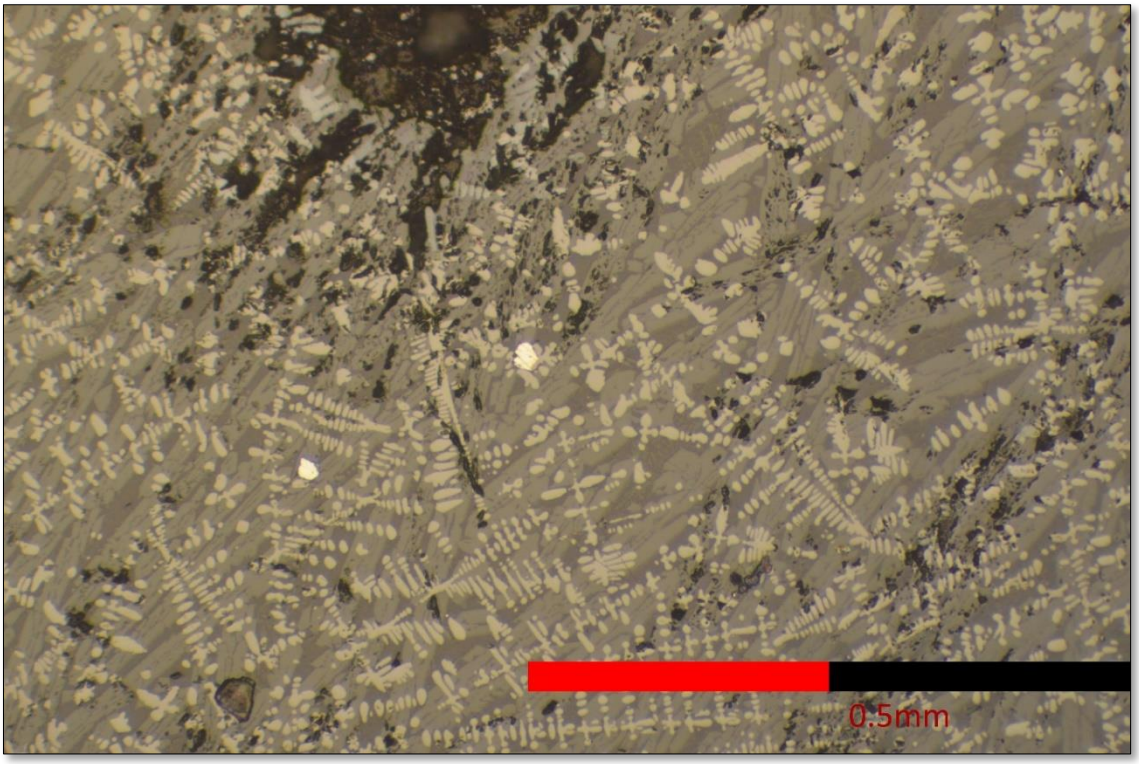

Plate 52, DSW 1170 1, fayalite laths

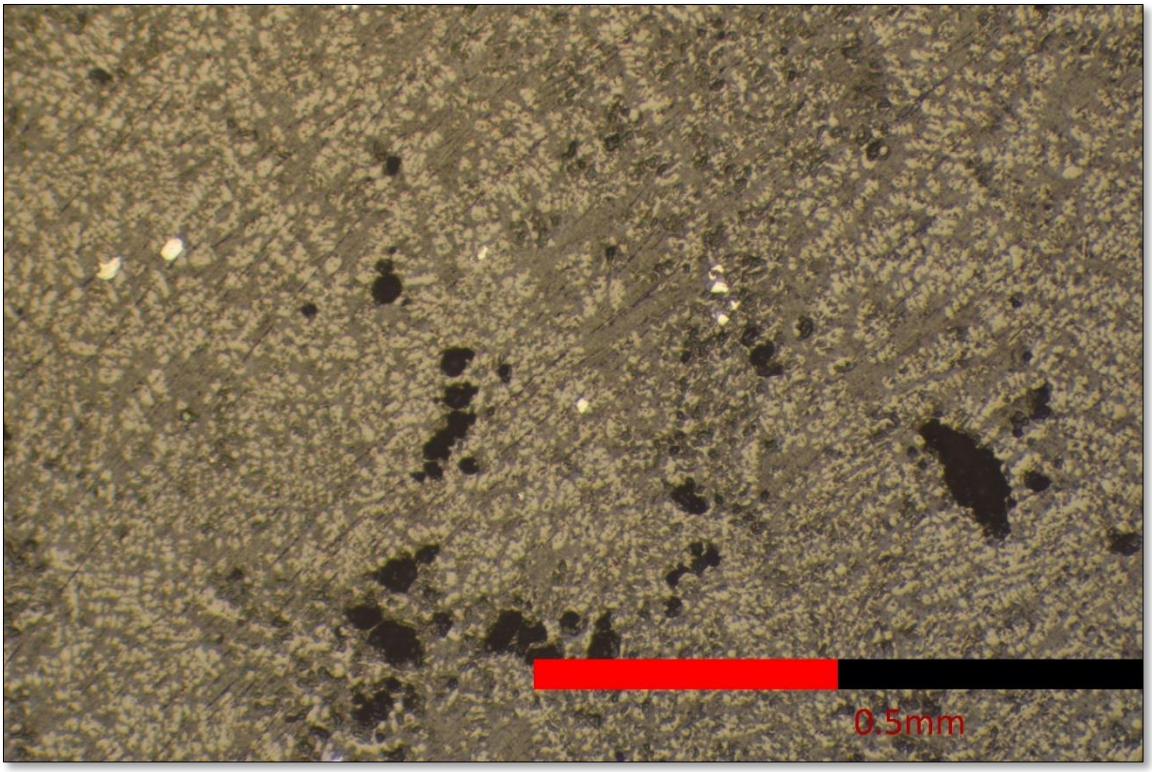

Plate 53, DSW 1039 1, metallic prills, globular wüstite dendrites

'Life History'

The slag from this site was produced from a slag tapping furnace based on the micro and macromorphology. The two types of tapped slag, tap and tube, from this site will have had to have been fully liquid to be able to be tapped therefore to study this and compare between the two related slag types the chemical analysis will be used to determine the viscosity and liquidus temperature. The high levels of free iron oxide in these samples would indicate that the slag would have been more liquid, the chemical analysis will be used to study whether the slag was too viscous to be tapped freely from the furnace.

Chemical composition

The samples from this site have a high level of iron oxide with four (DSW 1035 2, 1035 3, 1039 2 and 1064 1) having very high levels. All of the samples have elevated levels of alumina and calcium suggesting these are related and therefore may be the result of the ore composition. The phosphorus level is quite low indicating the metal produced would not have a phosphoric composition. The calcium level is slightly elevated which would have acted as a flux allowing for more iron to be reduced from the ore.

The liquidus temperatures from these samples cluster around the optimum 2 ranging from 1150-1175°C tailing towards a lower iron oxide composition. The slag from this site would have been free flowing at quite a low temperature (c.1200°C) because of the high levels of iron oxide. The RII for these samples shows that the smelt that produced them had a less reducing condition.

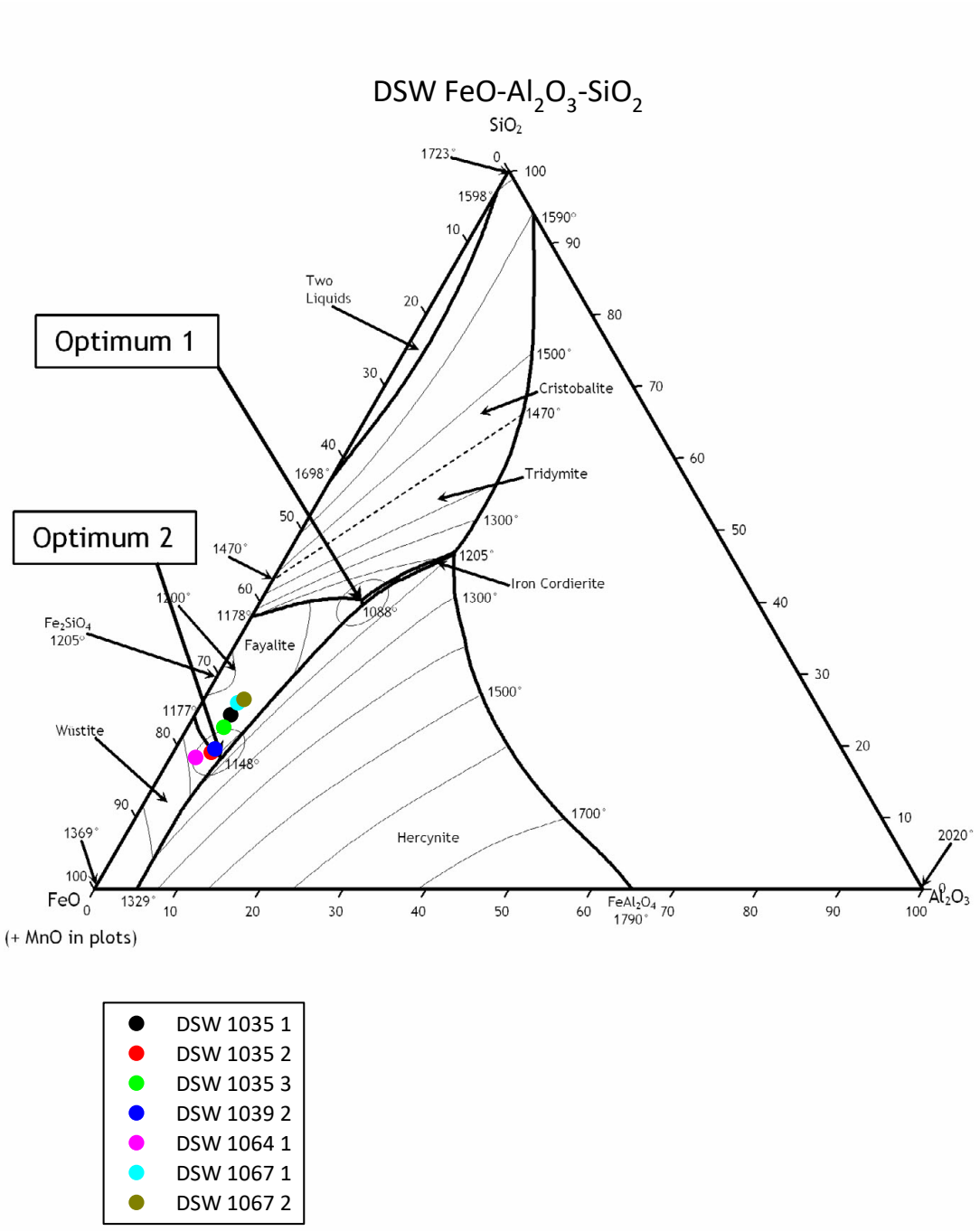

Figure 30, DSW FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
DSW 1035 1	0.7	0.9	4.1	22.1	1.4	1.8	3.5	b.d	b.d	65.5	100.0
DSW 1035 2	b.d	1.2	4.5	17.9	0.7	1.1	2.3	b.d	0.2	72.3	100.3
DSW 1035 3	0.6	0.9	4.3	21.5	0.5	1.1	1.6	b.d	0.3	70.0	101.0
DSW 1039 2	b.d	1.1	4.7	18.2	0.5	1.6	2.7	0.3	b.d	71.3	100.2
DSW 1064 1	b.d	0.7	2.9	16.6	0.8	1.7	6.0	b.d	b.d	71.9	100.5
DSW 1067 1	0.5	1.1	4.1	23.4	0.8	2.0	5.0	b.d	0.3	62.8	100.0
DSW 1067 2	0.5	1.2	4.5	23.5	1.1	2.1	6.0	b.d	0.4	61.2	100.5

Table 37, DSW composition

	1150°C	1200°C	1250°C	1300°C	1350°C
DSW 1035 1	18.1	12.51	8.87	6.43	4.76
DSW 1035 2	17.59	12.42	8.92	6.55	4.9
DSW 1035 3	22.35	15.47	11	8	5.94
DSW 1039 2	16.22	11.36	8.14	5.97	4.46
DSW 1064 1	10.15	6.98	5.09	3.79	2.87
DSW 1067 1	19.42	13.38	9.47	6.85	5.07
DSW1067 2	20.06	13.7	9.68	6.99	5.16

Table 38, DSW viscosity (Poise)

	RII
DSW 1035 1	0.81
DSW 1035 2	0.59
DSW 1035 3	0.73
DSW 1039 2	0.61
DSW 1064 1	0.55
DSW 1067 1	0.88
DSW1067 2	0.91

Table 39, DSW RII (Green – less reducing, Red - More reducing)

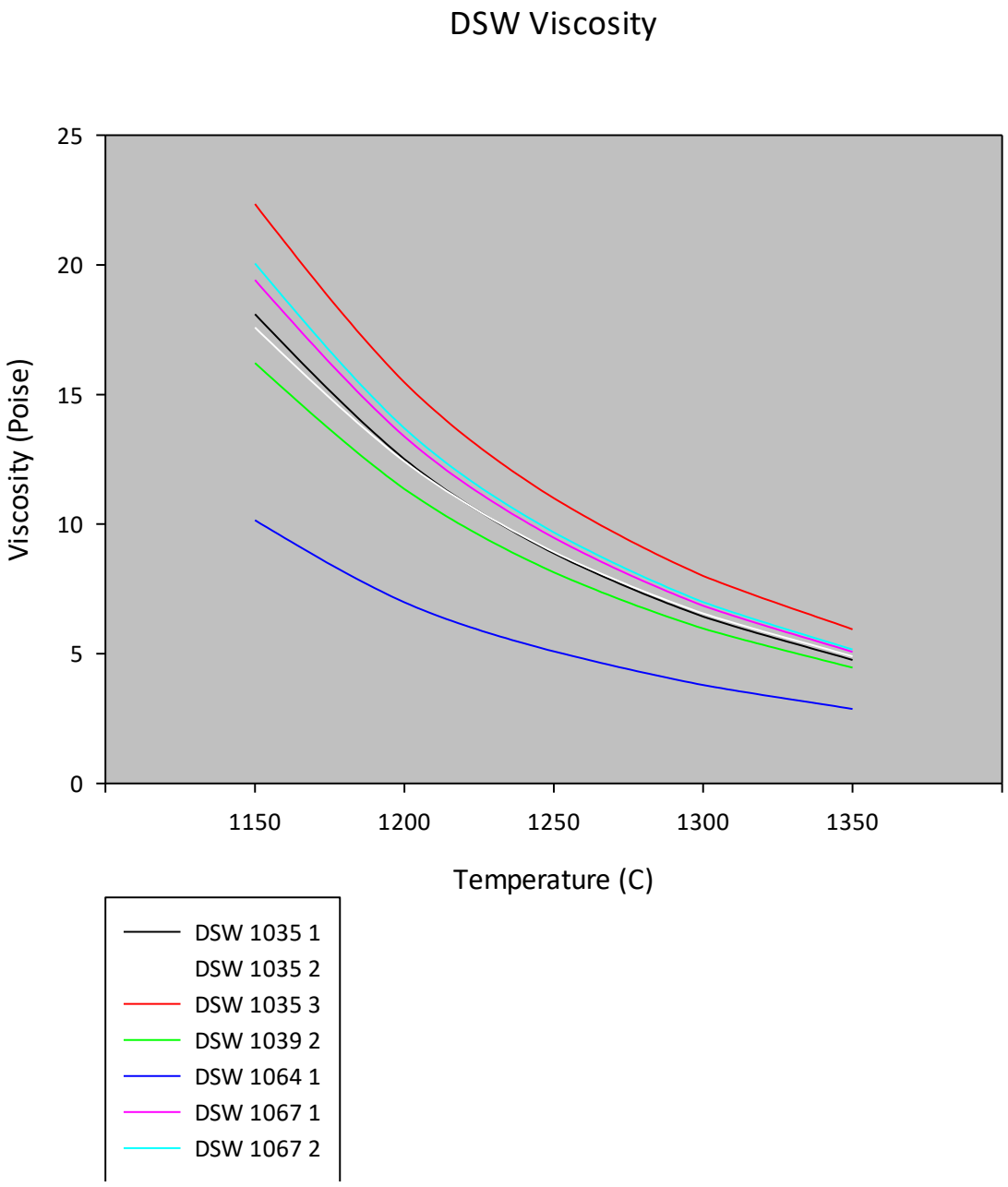

Figure 31, DSW Viscosity (Poise) vs Temperature (°C)

4.2.3 Stockbury, Kent (STO)

This site consisted of a number of sunken shaft furnaces associated with sunken floor structures. Ceramic evidence dated these furnaces to around a hundred years of activity from c.50 BC to c.50 AD. The analysis of the slag and smelting remains suggests a transitionary type of smelting between non tapping and tapping furnaces. The number of furnaces suggest a specialised smelting site using an evolved form of furnace.

Macromorphology

The slag from this site was received as cut samples therefore macro analysis must rely on the excavation report which is, summarised below. The smelting slag from this site has been characterised into four diagnostic groups, tap slags, furnace slag cakes, amorphous furnace slag and shaped/curved slag. The tap slag assemblage is mostly made up of small fragments with characteristic ropey flow marks on the upper surface and smooth undulating bases. Some of these have large voids towards the upper surface suggestion rapid cooling not allowing trapped gas to escape. Some of the slag fragments have trapped stones and furnace lining fragments in the base which suggest that the furnaces were reused and damaged furnace lining was lying around the front of the furnace while it was in operation. Furnace slag cakes dominated the assemblage in terms of weight and are the largest surviving fragments. There are two main types of slag cake, a more dense cake with few charcoal impressions and less dense with more charcoal impressions and frequent small runs of slag. Most of these masses have concave upper surfaces which may indicate where the bloom formed. The more dense slag is indicative of where the slag was very fluid and pooled at the base of the furnace where there was little charcoal. The less dense cakes were formed at the bottom of the furnace flowing through and trapping the charcoal when it solidified. Both of these types have smooth bases suggesting they formed on concave furnace bases. The final main type of slag is amorphous furnace slag which has broken edges and has few of the original surfaces remaining. These masses contain very

frequent inclusions or impressions of charcoal, but where the original surface remains it is more solid and dense (Girbal in Allen *et al.* 2013).

Micromorphology

The fayalite in the slag from this site is in the lath form but with some samples having areas of blocky crystals present. Therefore there is slag which cooled rapidly in some cases and over a moderate gradient in others. This would indicate that either the slag from the same smelt cooled at different rates at different points in the smelt or that there were different types of smelt being carried out. The wüstite is present as frequent fine skeletal dendrites, this indicates that there was a low level of reducing gases. This meant that it was not a very efficient process to produce metal from the ore. It also means that the iron produced would have had a low level of carbon. The high volume of free iron oxide would have made the slag less viscous at a temperature close to its liquidus temperature. The microstructure of the slag from this site suggests that a slag tapping furnace was in operation which sacrificed volume of iron produced to flux the slag allowing it to flow from the furnace. One of the samples has two factors which suggest key details of how the furnace was operated. It has more blocky fayalite laths with some blocky crystals which suggest it cooled over a moderate cooling period. It also has a freeze line of magnetite which shows where a layer of slag solidified in an oxidising atmosphere. This could represent where a furnace was opened to tap slag out, opening the front of the furnace caused cool air to flow in solidifying this surface and oxidising the slag forming magnetite.

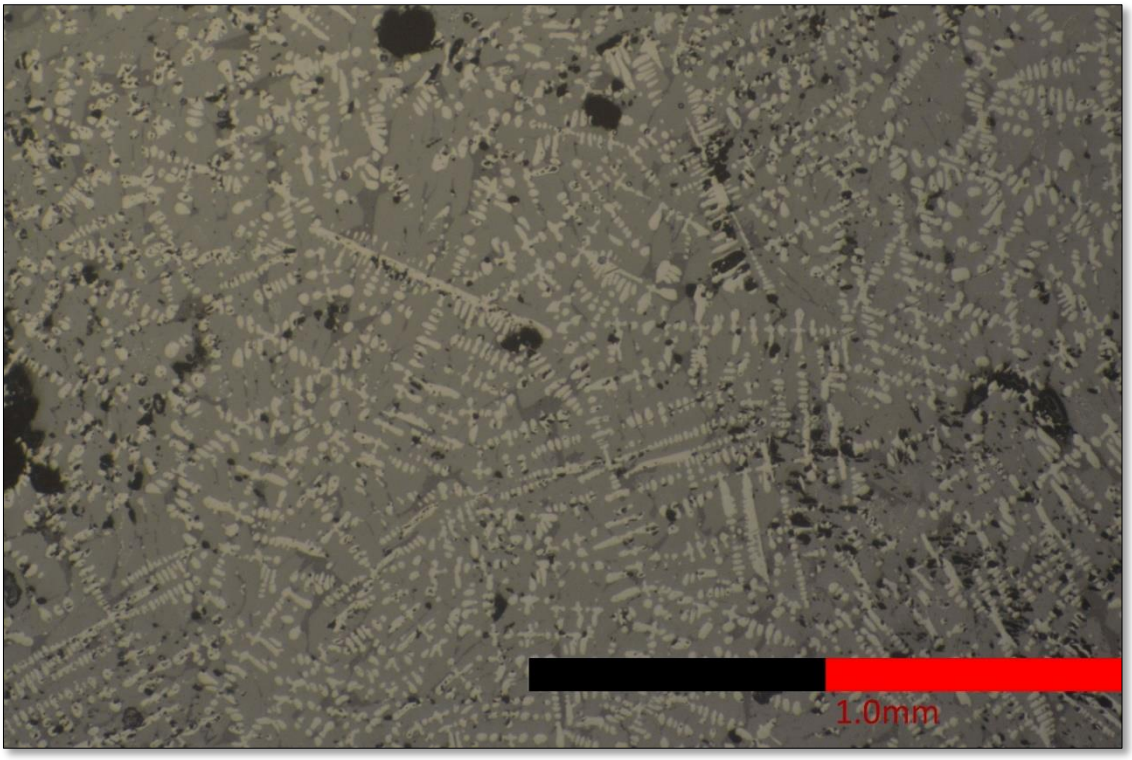

Plate 54, IW 061 - blocky fayalite laths and developed wüstite dendrites

'Life History'

The slag from this site was received as pre cut samples, however the site report has an in depth discussion of the slag revealing this site is very important as it has both non-tapping and tapping furnaces. The micromorphology of the slag from this site is dominated by fayalite laths, there are some samples which had blocky fayalite. The difference between these two microstructures may represent the difference between the tapping and non tapping furnaces. Determining the liquidus temperature and the viscosity of the slag with these microstructures will help determine what process the slag was from. If the samples received can be attributed to one of these processes then studying the chemical composition can be used to determine whether they used the same raw materials and different methods or different raw materials and the same methods. The presence of freeze lines of magnetite indicates the exposure of the slag while liquid to an oxidising environment and what effect that would have had on the slag will also be studied with chemical analysis.

Chemical composition

The composition of the slag from this site appears to be correlated to the composition of the ore, the samples with more elevated alumina also have elevated levels of calcium. The iron oxide content of the samples from this site are high but within the expected range (Pleiner 2000, 252). Sample IW 061 has a lower level of calcium and a higher level of iron oxide than the other two samples as the iron has to be sacrificed to flux the slag. The phosphorus content is relatively high suggesting an input from the ore, sample IW 061 has the lowest phosphorus content corresponding to the lowest alumina and calcium content. The variation is quite minor, which suggests a change in the amount of contribution from the ore to the slag rather than a different ore being used.

The estimated liquidus temperatures for these samples range from 1175°C to 1150°C, with the variation being controlled by the iron oxide and alumina contents. All of the slag would have been free flowing at 1250°C. The RII of the slag samples are both slightly less and slightly more reducing.

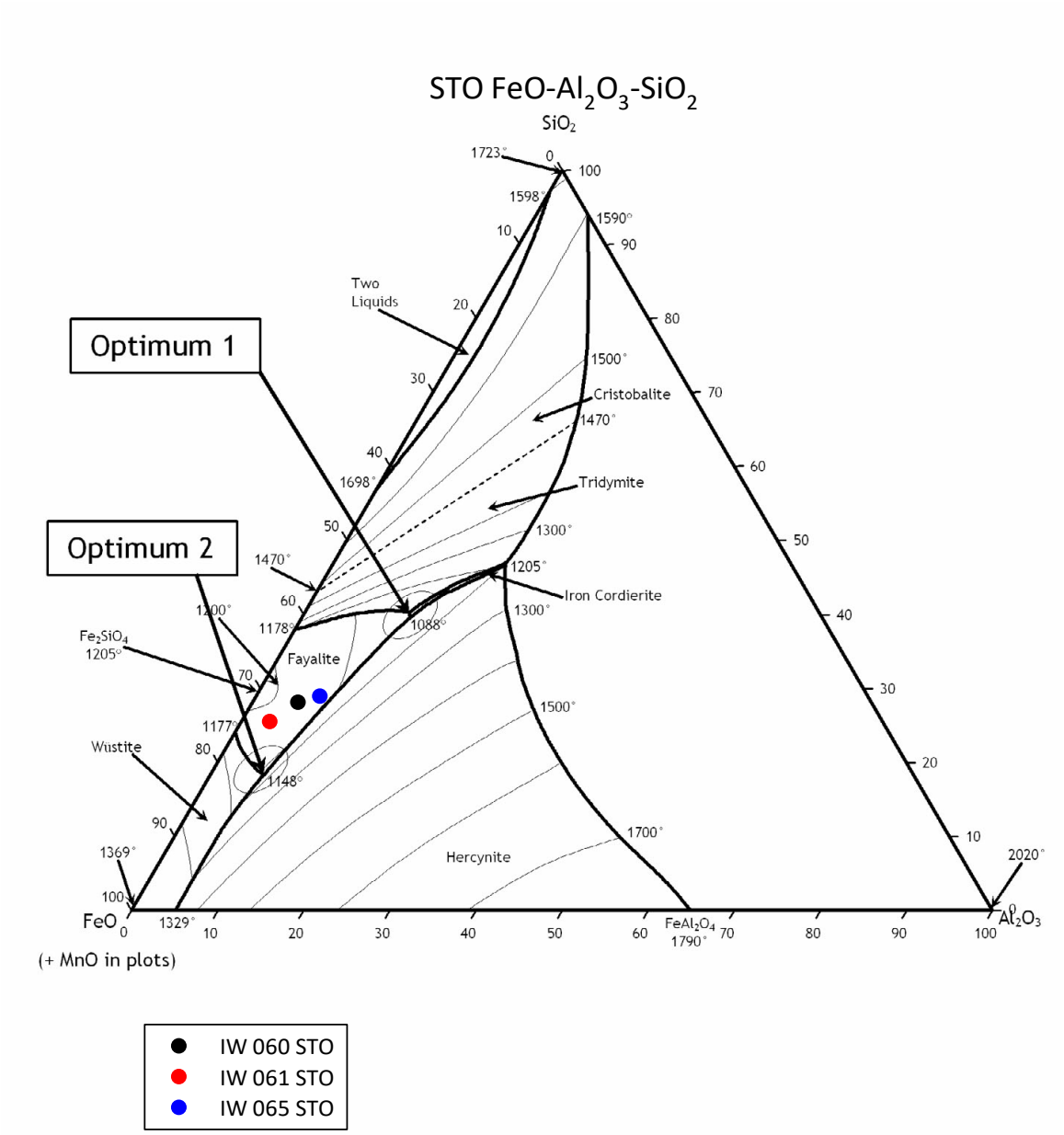

Figure 32, STO FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
IW 060 STO	b.d	b.d	4.9	26.1	1.8	1.0	2.8	b.d	0.5	62.8	100.0
IW 061 STO	b.d	0.4	3.1	24.3	1.2	0.4	1.2	b.d	0.4	68.9	100.0
IW 065 STO	b.d	0.4	6.8	26.5	2.0	1.4	3.3	b.d	0.6	59.0	100.0

Table 40, STO composition

	1150°C	1200°C	1250°C	1300°C	1350°C
IW 060 STO	24.29	16.44	11.44	8.15	5.93
IW 061 STO	22.65	15.65	11.09	8.04	5.95
IW 065 STO	33.48	22.34	15.32	10.78	7.75

Table 41, STO viscosity (Poise)

	RII
IW 060 STO	0.99
IW 061 STO	0.84
IW 065 STO	1.06

Table 42, STO RII (green – less reducing, red – more reducing)

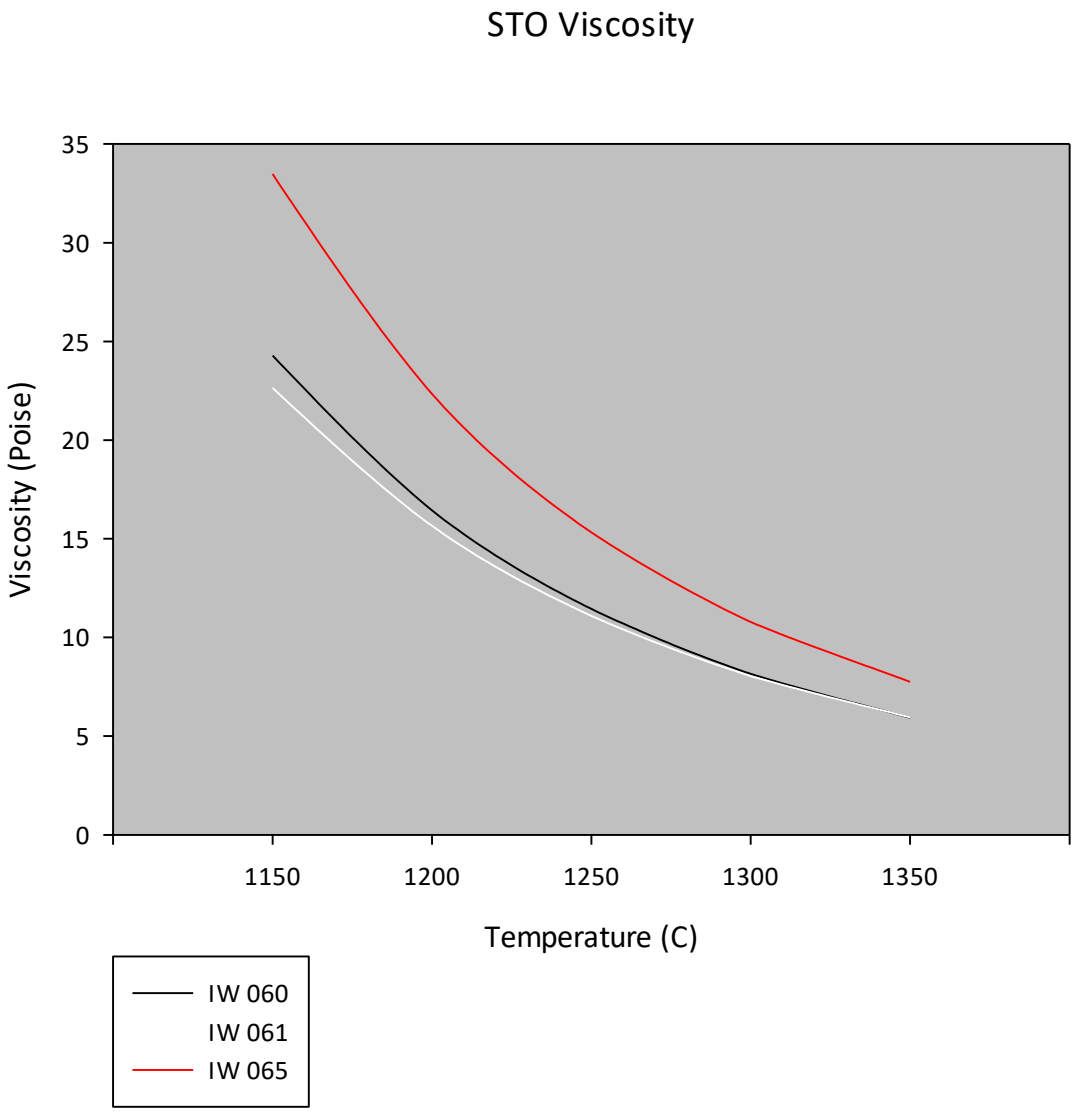

Figure 33, STO viscosity vs temperature (°C)

4.3 ROMAN SITES

4.3.1 Worcester Football Club, Worcester (WFC)

The slag was recovered from contexts dating to the 1st and 2nd century AD, no furnaces were found on this site but the quantity of material and the lack of evidence for weathering suggests the furnace was located close to this site.

Macromorphology

The slag assemblage from this site is formed of three main types of slag, furnace slag, tap slag and tube slag. All of the furnace slag from this site has no external surfaces remaining, meaning it is not possible to estimate the size and shape of the furnace from this source. The furnace slag is rough and irregular with frequent voids which suggest that the slag flowed over and around charcoal at the base of the furnace which was then burnt out. Tap slag from this site is in two forms, 'classic' tap slag with ropey flow marks on the upper surface and a flat 'slab' of slag. This slab form of slab was formed by slag which was liquid enough to pool forming a flat surface but cooled rapidly enough to trap bubbles in the upper portion. The base of this mass has fragments of tap slag trapped within it, showing that the slag had been tapped over material already removed from a furnace. Several examples of slag tubes were recovered from this site, there are individual tubes with different diameters and stacks of multiple tubes. These variations indicate that multiple furnaces were in operation. One of the stacks of furnace tubes (context 376) contained at least eight slag tubes agglomerated together, the tubes are of slightly different diameters indicating they flowed into different sized voids. The assemblage is completely consistent with what would be expected from slag tapping furnaces.

Plate 55, Close up of slag tube stack

Plate 56, Furnace slag

Plate 57, Tap slag

Micromorphology

The microstructure of the slag from this site is quite consistent across the different samples. The silicate is present as fayalite particularly in the lath form. This dominance of the lath form of silicate indicates the slag cooled rapidly over a short thermal gradient.

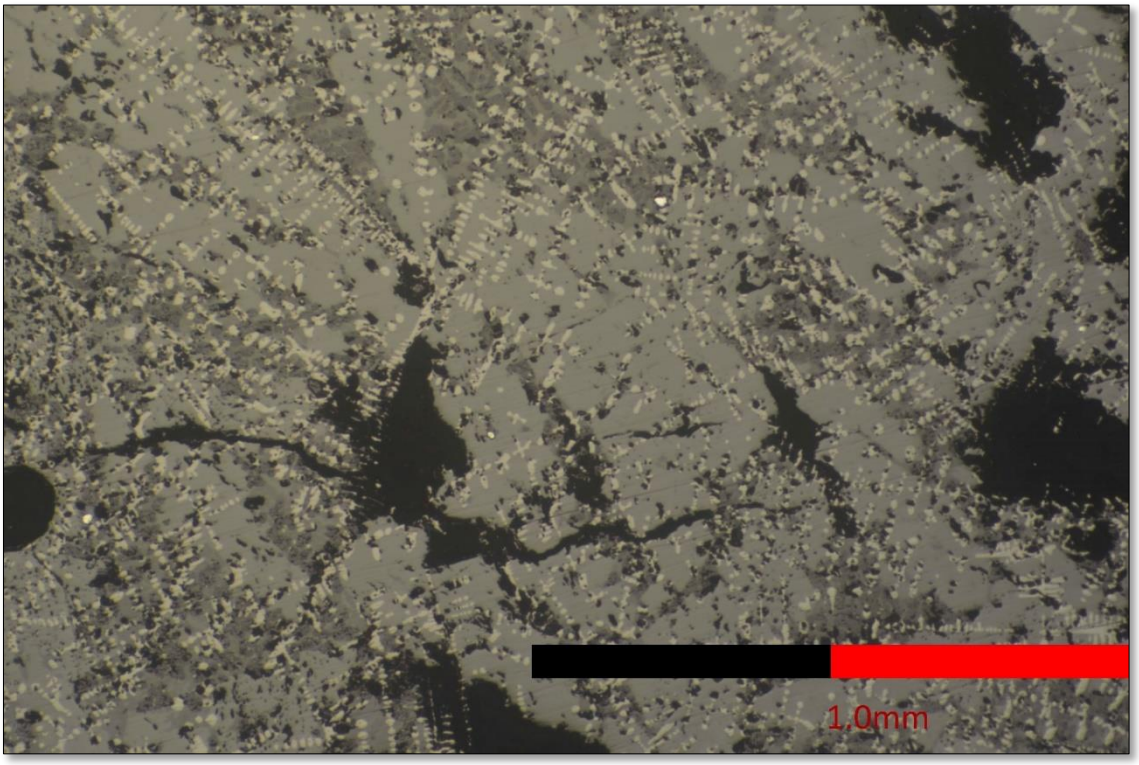

Plate 58, WFC 352 1, blocky fayalite laths, wüstite dendrites and occasional metallic prills

The form of the wüstite is consistent between samples but the volume varies considerably. The amount of wüstite relates to the amount of reduction gas present during the smelt, high presence of wüstite relating to a low reducing atmosphere and low wüstite relating to a higher reducing atmosphere. A higher reducing atmosphere also relates to more carburising conditions which could have led to iron with a higher carbon content.

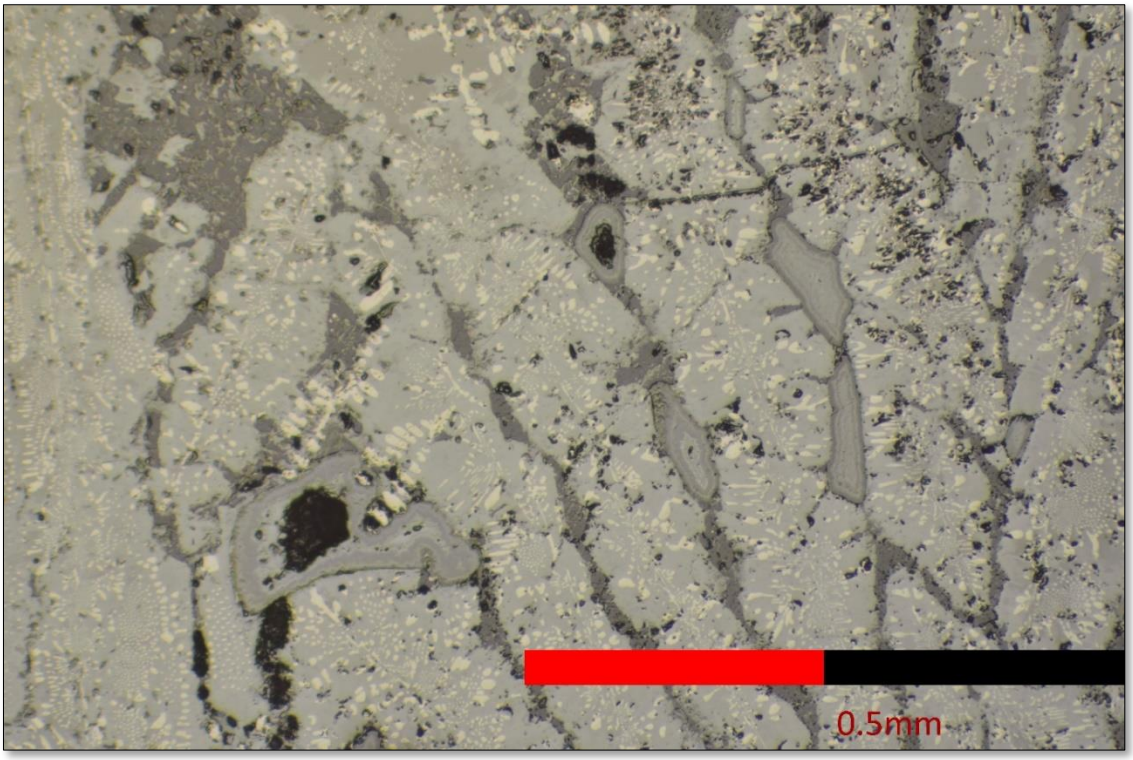

Plate 59, WFC 463 1, fayalite with fragmentary wüstite

There are some examples of the higher oxide form of iron oxide, magnetite, forming along freeze lines especially in masses of tap slag with multiple flows over each other. This was formed by the liquid slag solidifying in a fully oxidising environment. Metallic prills are present in one of the samples of tube slag, the amount of these indicates that metal was still being reduced from the ore.

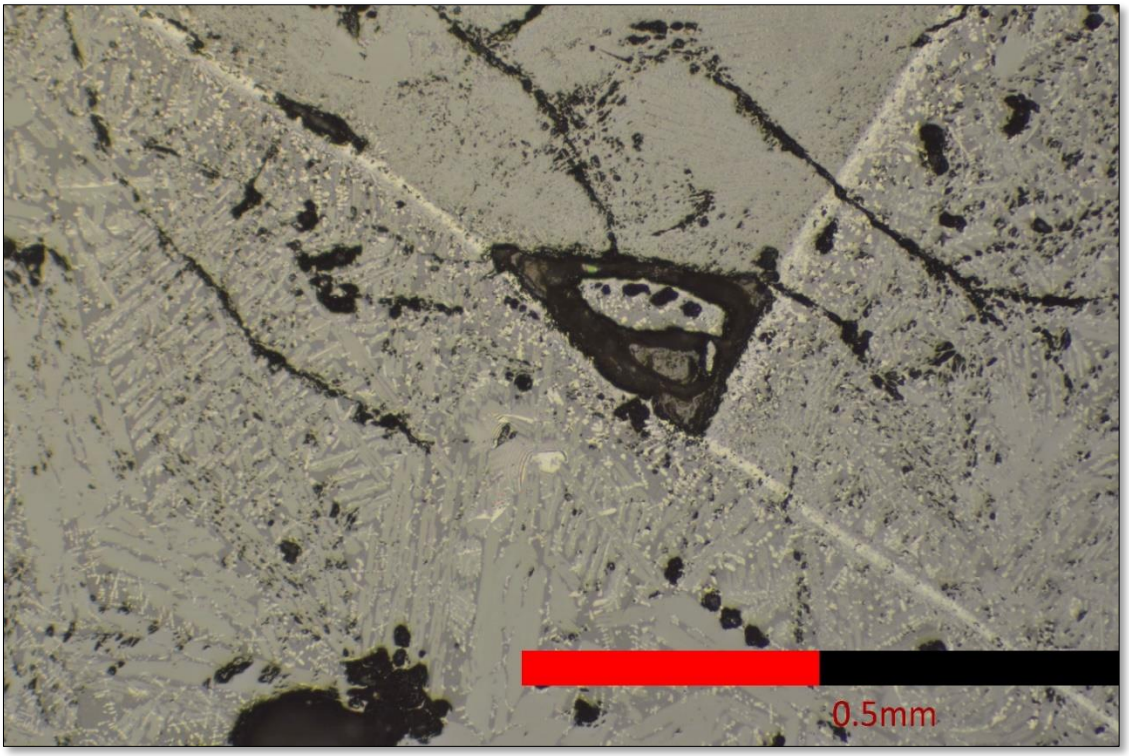

Plate 60, WFC 376 1, magnetite freeze lines

'Life history'

Macromorphological analysis of the slag from this site revealed three forms of slag, tap, tube and furnace slag. Of these tap and tube would be expected to have fairly similar microstructures produced by the slag cooling rapidly. The micromorphology is consistent across the samples with very little variation between the different types of slag. This is especially interesting for the furnace slag which indicates this slag cooled rapidly despite the macromorphology which is normally associated with a slow cool. This could be because the slag was held fully liquid until it solidified rapidly, it could also be the result of the slag being continuously tapped from the furnace until the end of the smelt and the slag left in the furnace as the smelt ends and the temperature drops rapidly. The amount of wüstite present in the samples vary substantially which suggests a difference in the reduction conditions, this should have affected the viscosity of the slag significantly and given a consistently liquid macromorphology the changes in viscosity will also require

changes in the operating temperatures. The chemical composition of the slag will show the viscosity and liquidus temperature and whether these vary between the furnace slag which may be expected to be more viscous as it would have been formed after charging of ore would have finished.

Chemical composition

Most of the samples have an iron oxide content which is consistent within 7% two further samples are 6% higher and one which is 7% lower. This similarity of compositions indicates that there was a deliberate control in the reduction processes to have a consistent product. The levels of iron oxide are high but well within the expected range for bloomery smelting slag from Europe (Pleiner 2000, 252). The silica levels within the samples are also within the expected range but towards the higher end. The alumina contents are elevated and quite consistent the calcium levels are more varied indicating that the changes in the compositions are not caused by the same raw material. The elevated alumina is likely to be the result of increased contribution from the furnace lining.

The liquidus temperature of most of the samples are quite consistent around 1175°C, the higher iron oxide composition samples are slightly elevated but still below 1200°C. The slag began to be free flowing at 1250°C but would have been completely free flowing at 1300-1350°C. The RII of these samples shows that the furnaces were mostly more reducing but a small number were less reducing.

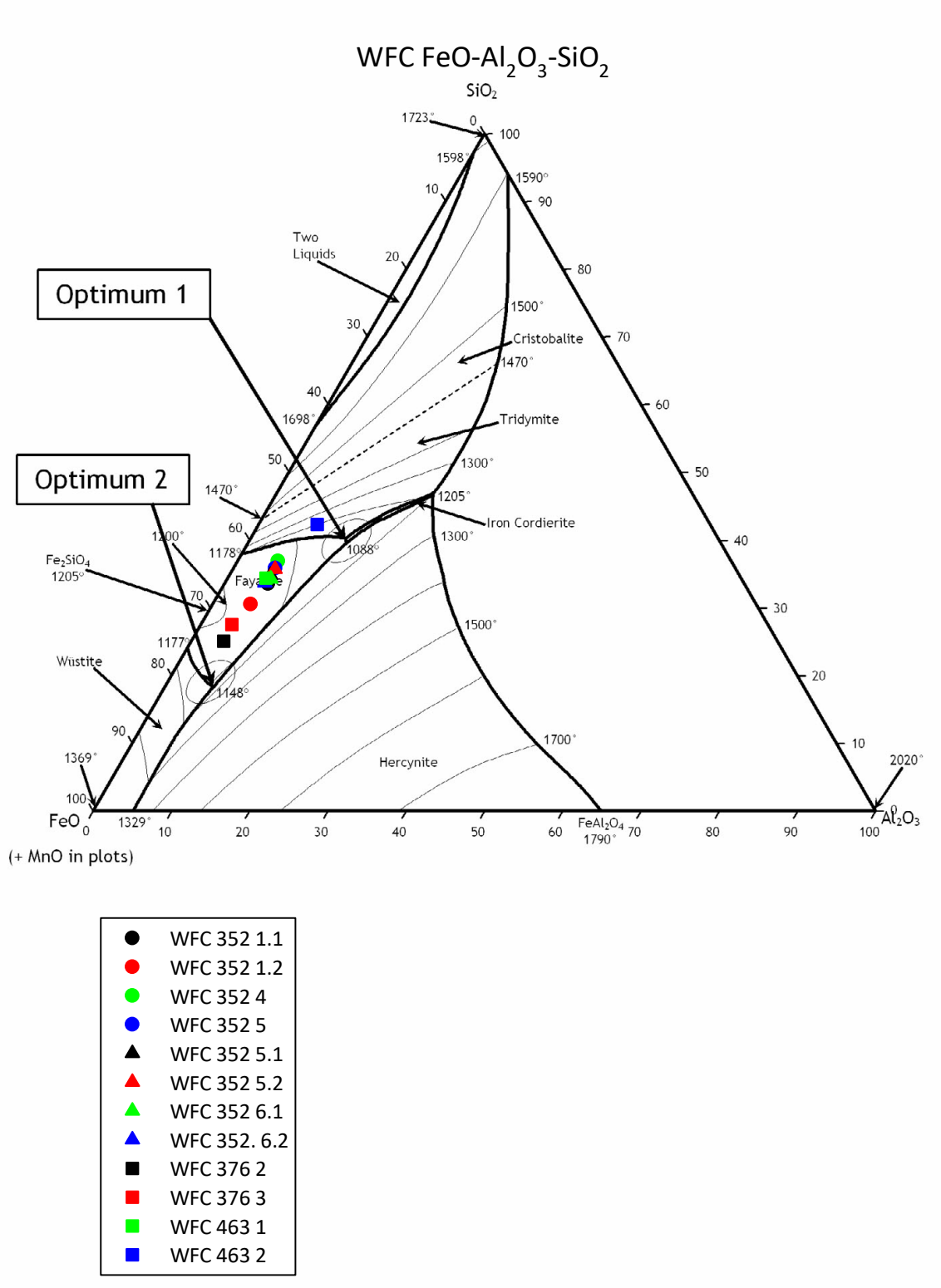

Figure 34, WFC FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
WFC 352 1.1	0.5	1.2	5.9	27.7	0.6	2.2	2.5	b.d	b.d	59.8	100.3
WFC 352 1.2	0.6	1.3	5.2	26.0	0.8	1.4	1.7	b.d	b.d	63.5	100.5
WFC 352 4	0.4	1.2	5.5	31.9	1.7	1.6	1.5	0.3	b.d	57.5	101.5
WFC 352 5	0.8	1.3	5.7	29.7	0.8	1.9	2.5	0.3	b.d	57.7	100.5
WFC 352 5.1	0.5	1.2	5.6	28.5	0.7	2.1	2.6	0.4	b.d	58.9	100.4
WFC 352 5.2	0.7	1.2	5.7	29.7	1.1	1.8	2.5	b.d	0.3	57.6	100.7
WFC352 6.1	0.6	1.6	5.9	28.5	0.9	1.9	2.3	b.d	b.d	58.6	100.3
WFC 352 6.2	0.6	1.4	5.4	28.0	1.1	1.8	2.4	b.d	0.4	60.0	101.1
WFC 376 2	0.6	1.0	4.5	21.4	0.6	1.0	1.3	0.2	0.2	69.9	100.6
WFC 376 3	1.2	1.2	4.4	22.5	1.6	1.2	1.5	b.d	b.d	69.1	102.7
WFC 463 1	0.4	0.7	5.2	30.9	b.d	1.3	1.7	b.d	b.d	60.1	100.3
WFC 463 2	0.8	0.8	7.9	36.1	0.9	1.7	2.7	0.7	b.d	50.2	101.9

Table 43, WFC composition

	1150°C	1200°C	1250°C	1300°C	1350°C
WFC 352 1.1	33.73	22.63	15.61	11.04	7.98
WFC 352 1.2	30.38	20.61	14.36	10.25	7.47
WFC 352 4	45.51	30.12	20.5	14.32	10.23
WFC 352 5	36.75	24.54	16.85	11.86	8.54
WFC 352 5.1	33.81	22.69	15.65	11.06	8
WFC 352 5.2	39.04	26.03	17.84	12.54	9.01
WFC 352 6.1	38.65	25.67	17.8	12.55	9.05
WFC 352 6.2	35.39	23.8	16.45	11.65	8.44
WFC 376 2	23.32	16.16	11.48	8.34	6.19
WFC 376 3	23.79	16.43	11.63	8.43	6.24
WFC 463 1	35.68	23.81	16.34	11.49	8.27
WFC 463 2	68.1	43.56	28.72	19.47	13.53

Table 44, WFC viscosity (Poise)

	RII
WFC 352 1.1	1.11
WFC 352 1.2	0.98
WFC 352 4	1.32
WFC 352 5	1.23
WFC 352 5.1	1.16
WFC 352 5.2	1.23
WFC 352 6.1	1.16
WFC 352 6.2	1.11
WFC 376 2	0.73
WFC 376 3	0.78
WFC 463 1	1.23
WFC 463 2	1.72

Table 45, WFC RII (Green – less reducing, Red – more reducing)

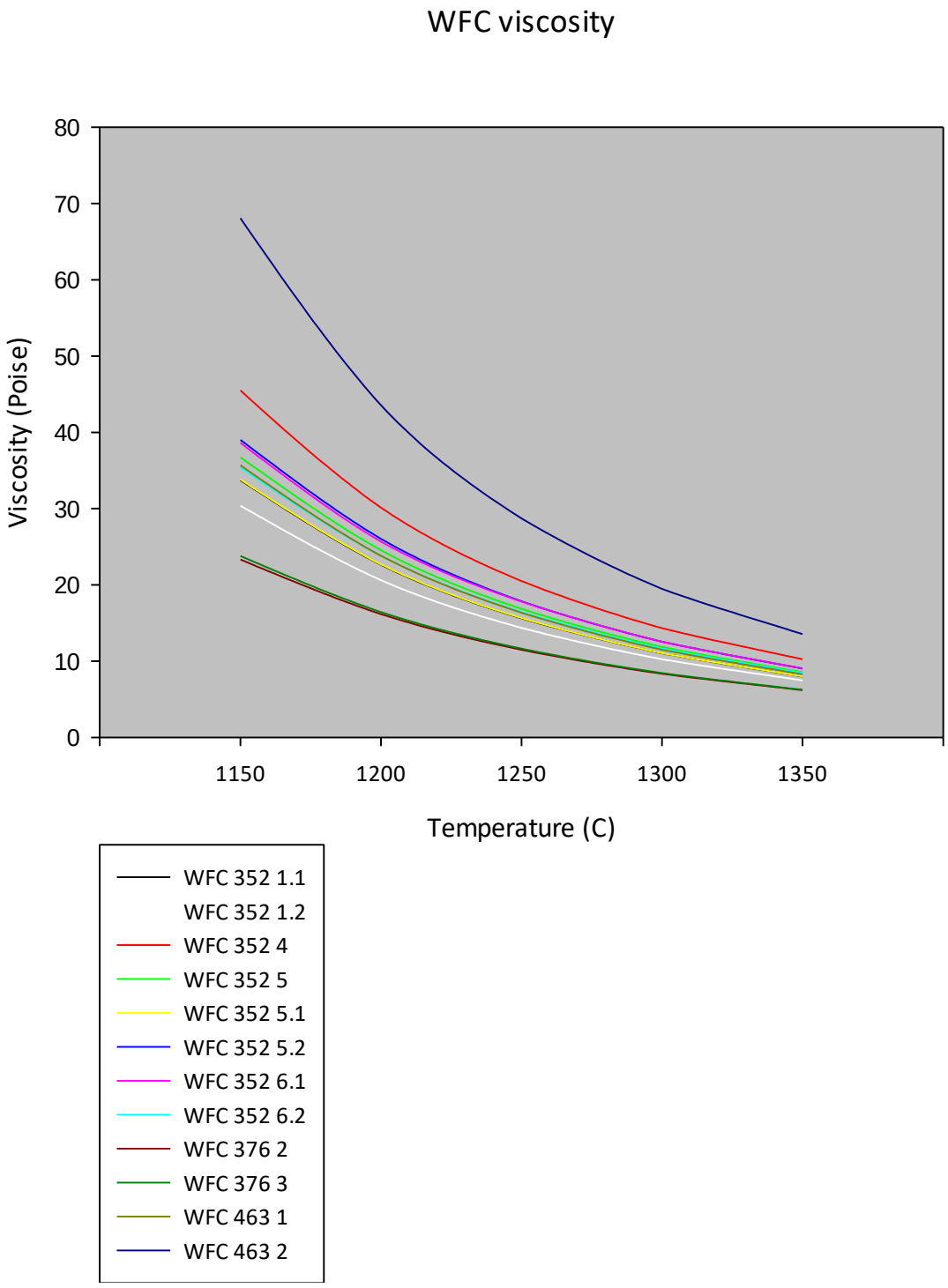

Figure 35, WFC viscosity (Poise) vs Temperature (°C)

4.3.2 Beauport Park, Battle (BP)

This site is one of the largest individual smelting sites in Roman Britain, the smelting area of the site has not been fully explored and no furnace remains have been found. The site was a specialist smelting site with associations to the *Classis Britannica*.

Macromorphology

A small assemblage of slag was recovered from this site. A large mass of dense slag was subsampled from the available assemblage. The mass is over 0.25m square with no evidence of any external surfaces, this indicates the furnace would have been larger than this. The mass has a large elongated void entering into the side of the mass, it has a rippled texture which reflects where the airblast forced through the mass of slag and would indicate the end of the smelt.

Plate 61, Airblast void in glassy mass (BP 4)

The mass is very dense and on sides damaged during sampling it is very glassy and has a number of fragments of charcoal in the lower portion. Also recovered were a number of fragments of tap slag, all have a smooth underside but the upper surfaces are in two different forms. As well as the ropey flow marks typical of tap slag there is also a sample which has a rippled upper surface. This indicates a meniscus formed on the surface of the slag while the slag underneath was still liquid leading to the surface becoming disturbed by the movement underneath.

Plate 62, Tap slag with rippled surface

Micromorphology

The micromorphology of the slag from this site is limited to two main phases, fayalite and a glassy phase, there is also a small amount of hercynite present in one of the samples. The fayalite is present as very fine laths within a large amount of glassy phase. This suggests

that the slag was cooled very rapidly forming fine needle-like laths, this combined with the low level of iron oxide contributed to the high volume of the glassy phase.

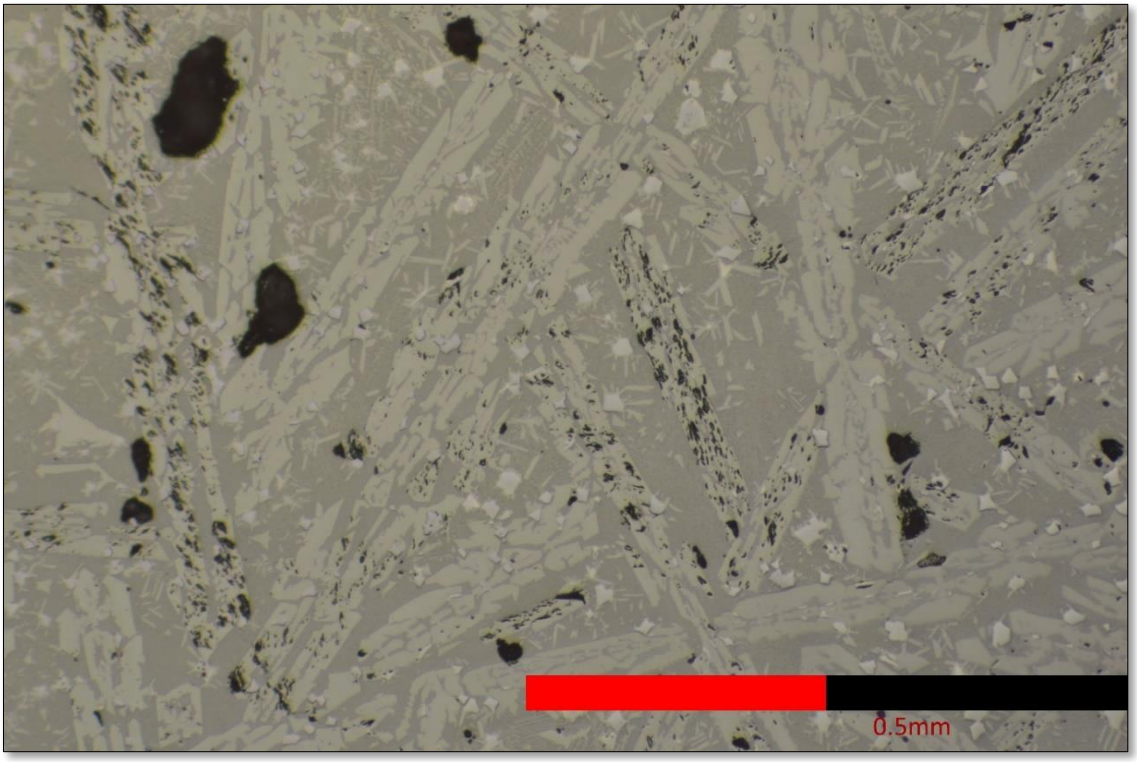

Plate 63, BP 2, fayalite laths, fine hercynite grains

One of the samples consists of only glass with large globular iron prills. A large droplet of iron suggests carburising furnace conditions and cast iron being formed.

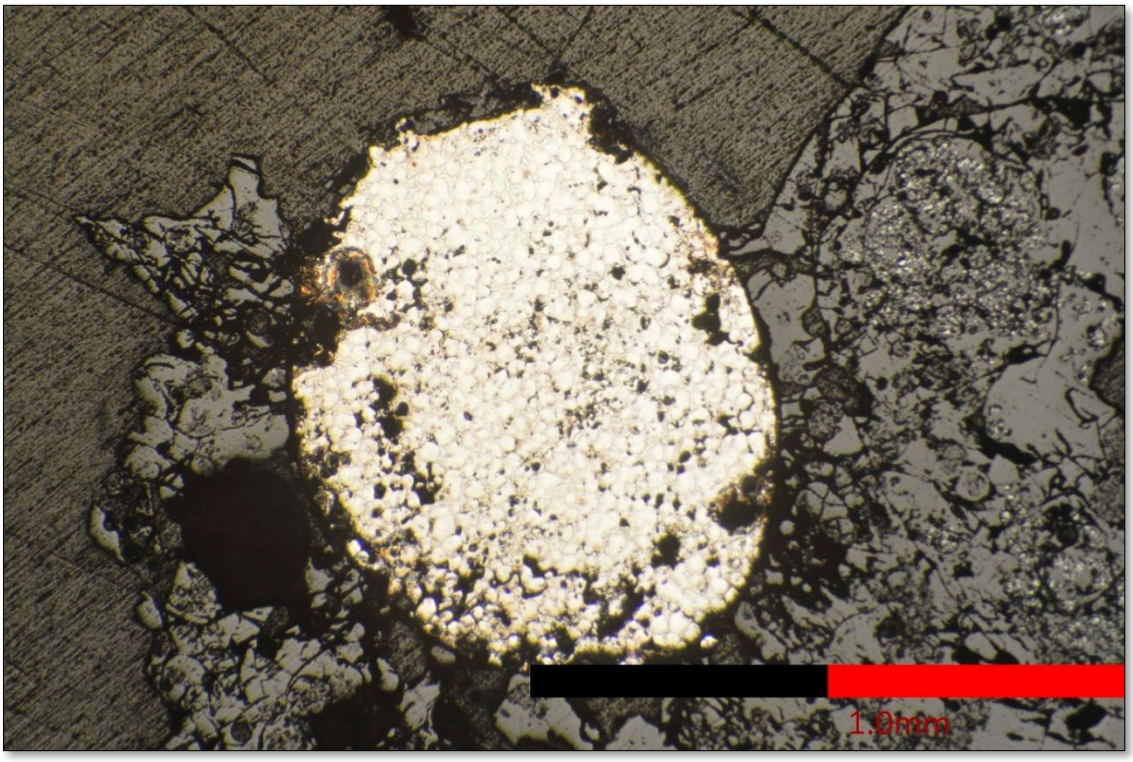

Plate 64, BP 4 cast iron prill

The microstructure of the slag suggests a highly controlled smelting process which was very effective at reducing the iron from its ore and had the potential to create iron with a high carbon content.

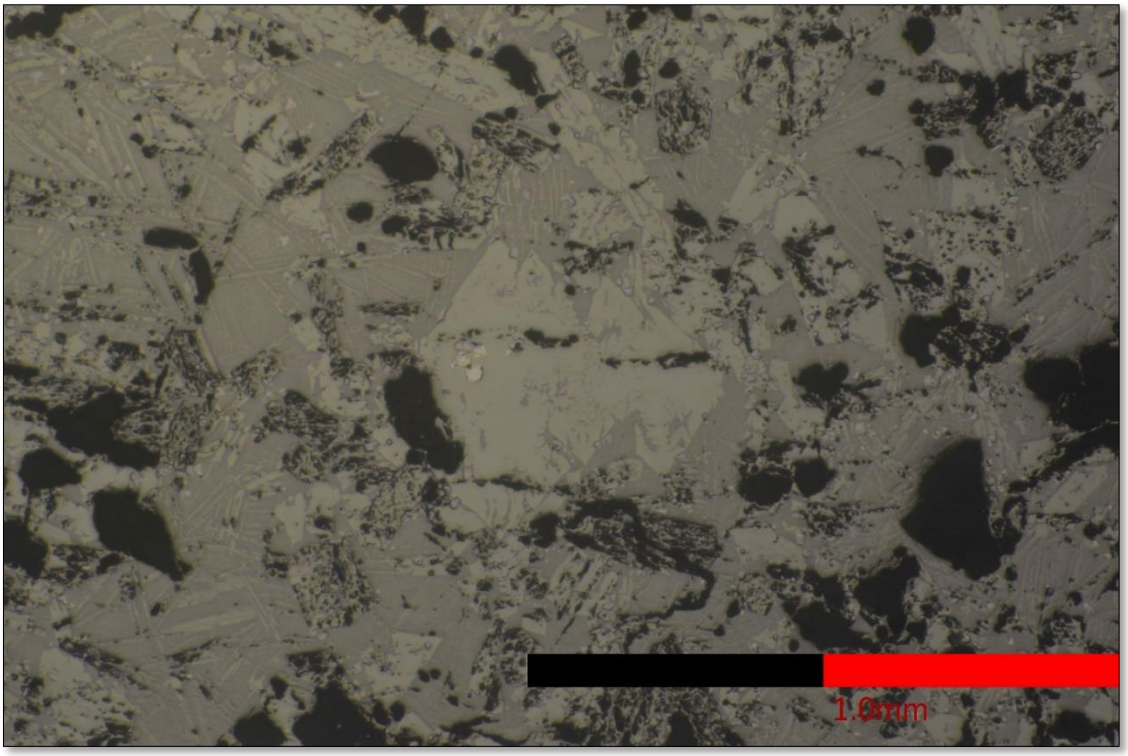

Plate 65, BP 1 lath fayalite and glassy composition

'Life History'

The evidence from the macro and micromorphological results of the small assemblage from this site is that a large slag tapping furnace was in operation on this site. The large mass of furnace slag was subsampled must have been produced in a large furnace, the micromorphology of this is very glassy with very fine silicate and a large metallic prill present. This mass has some features which are more typical of slag from an indirect smelting furnace. The chemical analysis and higher magnification of the SEM will be used to examine whether this slag was from a direct or indirect furnace. The rest of the assemblage has a more typical macromorphology for a direct smelting furnace, the micromorphology of the slag has no free iron oxide and is dominated by a high level of glass and very fine silicate laths. The low levels of free iron oxide indicate the reduction process was quite effective at producing metal but without this the slag may have a high

viscosity. The chemical analysis will be used to calculate the viscosity and the liquidus temperature.

Chemical composition

The small assemblage of samples from this site are quite consistent in some aspects, for example the alumina and silica content. However the calcium and iron oxide contents are quite different. The elements likely to have derived from the ore are consistent suggesting the same ore was being used. however the amount of iron oxide suggests different amounts of reduction in the furnace leading to more metal and possibly metal with a higher melting temperature.

The liquidus temperatures of the two samples are; BP 2 at between 1075°C and 1100°C, almost exactly optimum 1 and BP 3 at 1125°C. The low level of iron oxide in these samples mean that the slag would not have been free flowing below 1350°C. The RII of these samples show that this site was using furnaces with very reducing conditions.

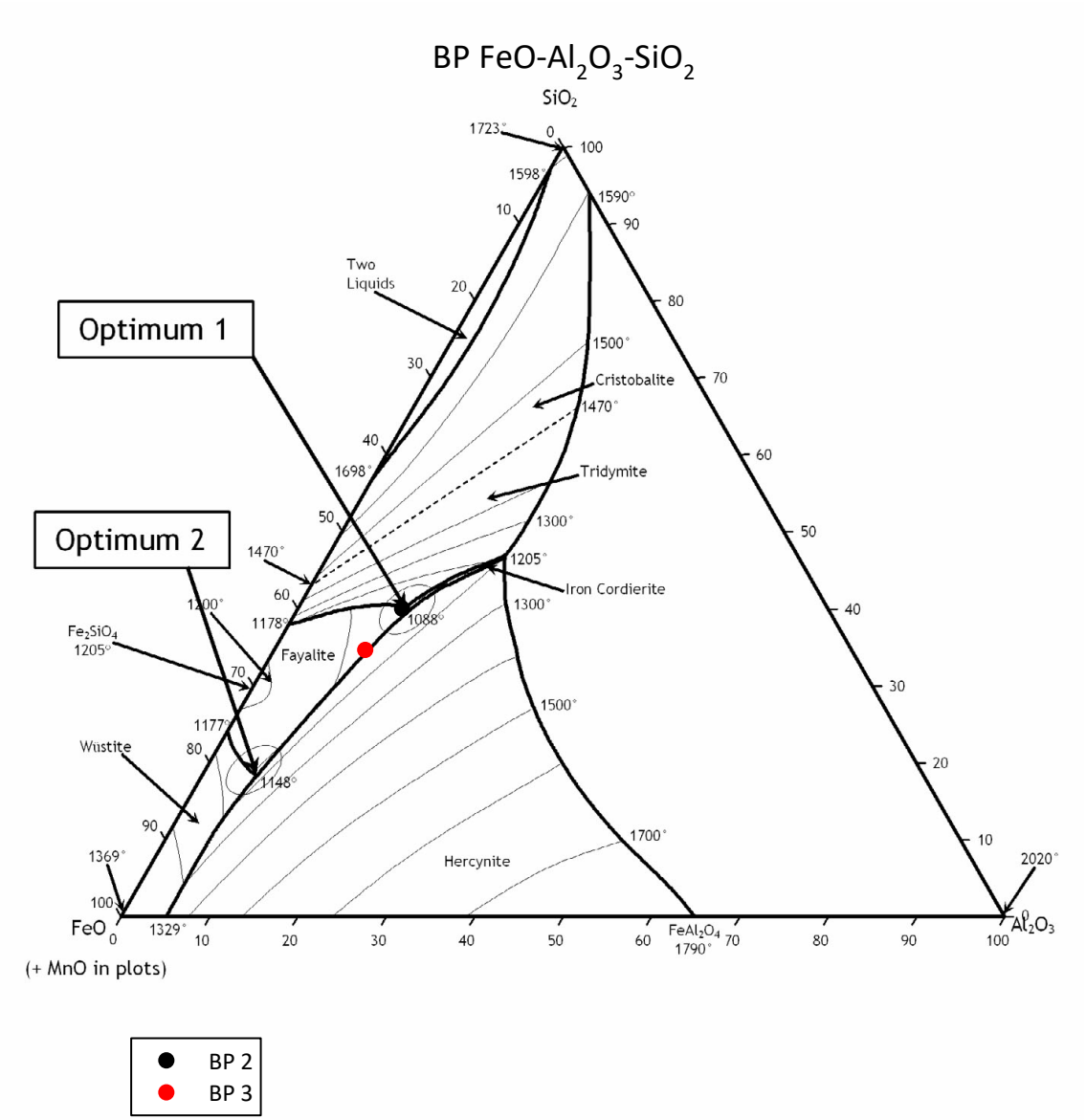

Figure 36, BP FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
BP 2	0.3	2.5	10.0	33.3	1.1	1.8	9.9	0.6	2.8	37.8	100.1
BP 3	0.4	2.0	9.5	31.1	0.9	1.5	4.2	0.6	2.0	48.1	100.3

Table 46, BP composition

	1150°C	1200°C	1250°C	1300°C	1350°C
BP 2	75.3	47.74	31.5	21.36	14.85
BP 3	72.07	46.5	30.9	21.15	14.84

Table 47, BP Viscosity (Poise)

	RII
BP 2	1.96
BP 3	1.48

Table 48, BP RII (Red = more reducing)

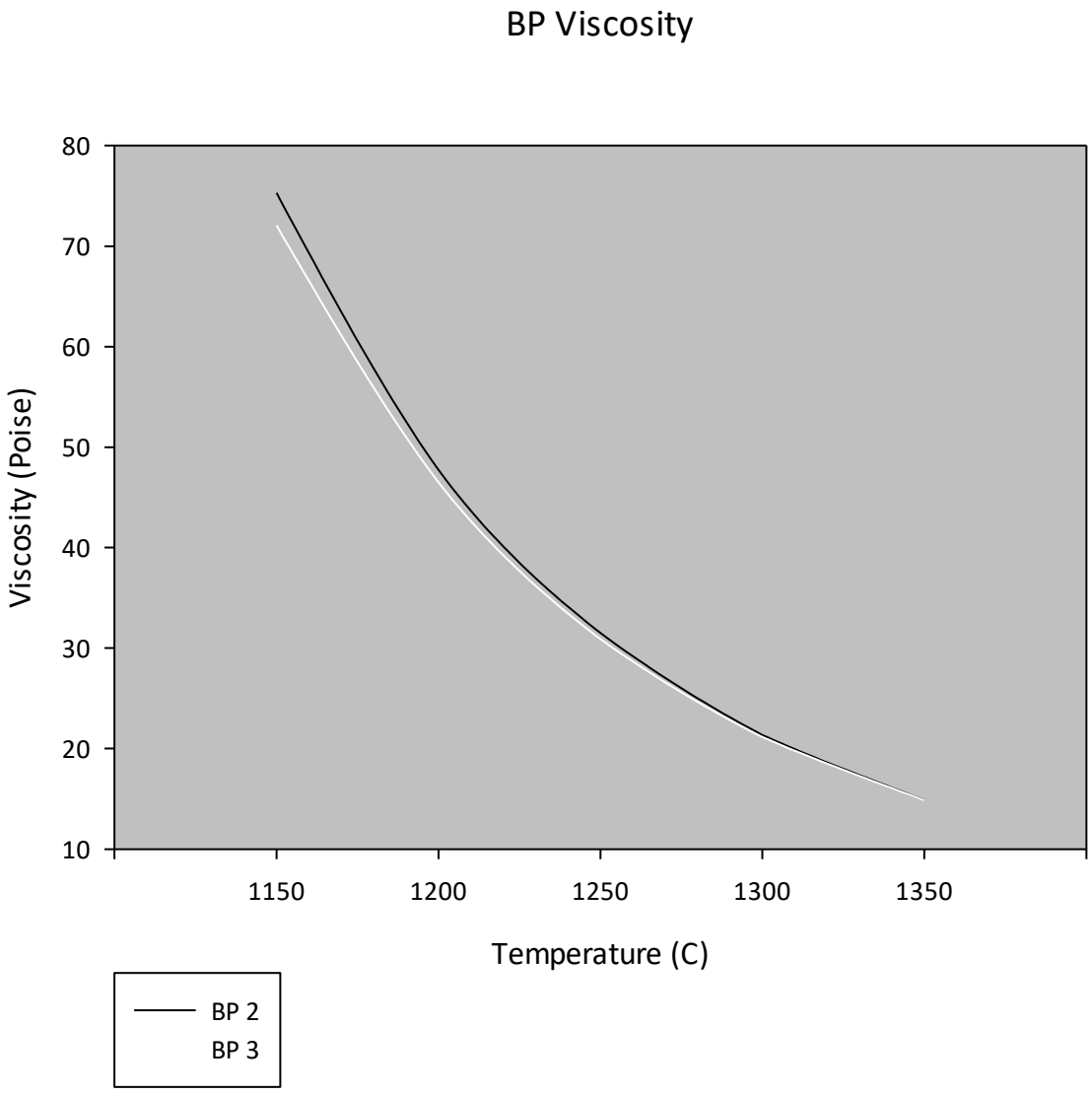

Figure 37, BP viscosity (Poise) vs temperature (°C)

4.3.3 Redding's Lane, Staunton (RDL)

The slag from this site was recovered from features dating to the early to middle Roman period. It is located next to a possible road and close to a signal station. The site appears to have been a ditched enclosed containing a series of furnaces, suggesting a specialist iron smelting site potentially dating from the 1st century AD.

Macromorphology

The assemblage of slag from this site is made up of furnace and tap slag. A large dense mass of slag recovered from context 602 has a number of liquid runs on the surface which show where the slag began to flow from the furnace.

Plate 66, Dense furnace slag mass

Other masses of furnace slag have large amounts of trapped or impressed charcoal which has partially burnt out leaving a high porosity. There is a final type of furnace slag which has a series of large circular wood impressions. This slag is formed by a liquid but viscous slag descending over round wood or charcoal leading to a dense mass of slag. This

indicates that the charge in the base of the furnace may have been supported above the base of the furnace. There is a small amount of tap slag present in this assemblage which fits the typical characteristics of tap slag, with ropey flow marks on the upper surface and a smooth underside. The slag assemblage from this site has indicators of both tapping and non-tapping furnaces. The large mass with evidence of flow on the surface suggests a broad opening for the tapping of slag.

Micromorphology

The iron silicate in the slag from this site is mostly in the lath form but there are examples in a more blocky form. Iron oxide is present as both skeletal and globular wüstite dendrites at a moderate to high frequency through all of the fully formed slags. Some of the samples are partially formed slag with mineral inclusions including unreduced ore. The microstructure of the slag from this site is dominated by microstructures which indicate that the slag was cooled rapidly with a short thermal gradient creating silicate laths and fine dendrites.

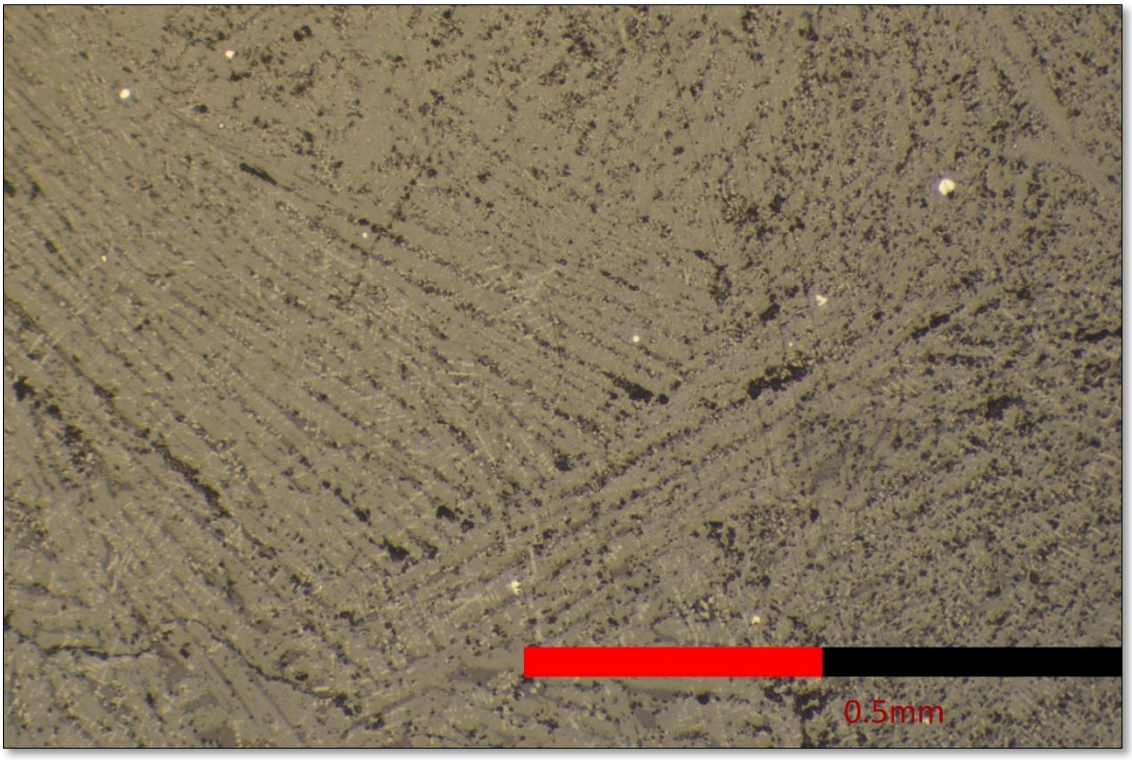

Plate 67, RDL 602 1 fine fayalite laths, skeletal wüstite and metallic prills

The moderate to high levels of free iron oxide show that the process is not particularly efficient or inefficient at reducing iron oxide to metallic iron. The number of samples which have partially formed slag or unreduced ore may be an indication that the smelt which created them was terminated early while the furnace was still being charged.

'Life History'

The combination of the macro and micro morphological results from this site shows that this site was operating a slag tapping furnace. When the furnace was opened at the end of the smelt it was still at operating temperature leading to the upper surface of one of the masses of furnace slag having evidence of flowing. This is the only mass which has blocky as well as lath form of fayalite, the remaining samples have fayalite in lath form, this shows a difference in the cooling rate. The liquidus temperature and viscosity difference between the furnace slag and the tapped slag will be studied using the chemical analysis.

Chemical Composition

The slag from this site has a high iron oxide composition with one sample (RDL 602 2) having a very high iron content. The effect of the very high iron content in this sample is that it has a low alumina and silica content, it also has a high phosphorus content. This sample appears to be quite different to the other analysed samples. The remaining samples have consistently typical silica, high alumina and elevated calcium contents. The low phosphorus levels of most of the samples suggests that the ore being used was not phosphoric and would have produced phosphorus free metal which could have been carburised. The alumina and calcium levels are elevated in the same samples suggesting the ore had the controlling influence on the composition rather than large inputs from the furnace lining.

The liquidus temperature of the slag is from 1150°C to 1200°C but with the outlier RDL 602 2 excluded then the range is restricted to 1150°C to 1175°C. The slag begins to become free flowing around 1250°C. The RII indicates that there was variation in the reducing conditions between less and more reducing conditions in the furnace.

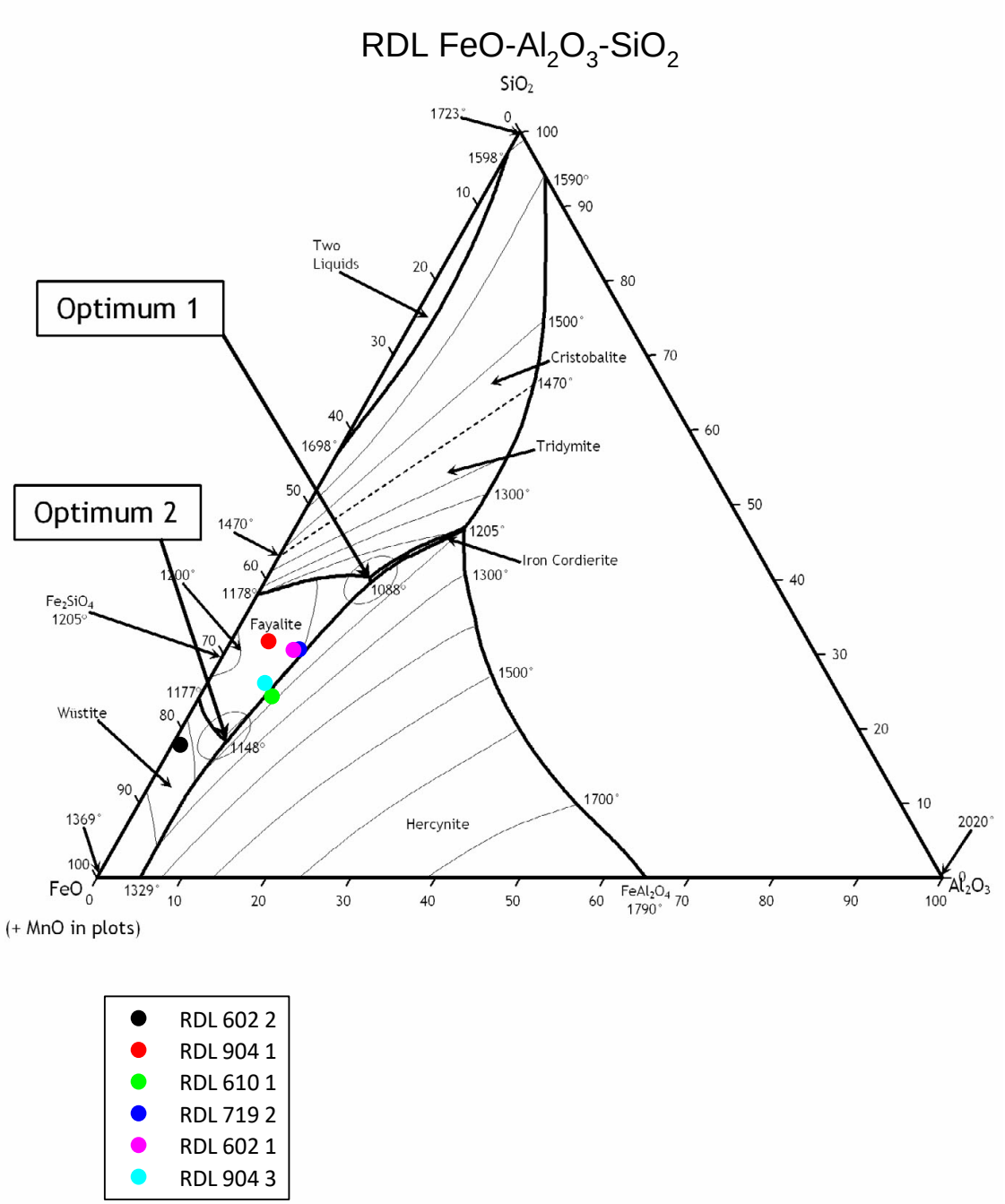

Figure 38, RDL FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
RDL 602 2	b.d	b.d	1.2	16.4	4.5	b.d	1.7	b.d	0.9	75.3	100.0
RDL 904 1	0.5	1.1	4.5	29.7	b.d	1.8	2.4	0.4	0.4	60.1	100.9
RDL 610 1	0.9	2.7	7.9	21.5	1.0	1.7	4.5	b.d	b.d	60.1	100.4
RDL 719 2	b.d	1.7	8.1	27.5	0.8	2.4	4.2	0.4	b.d	55.2	100.3
RDL 602 1	b.d	1.5	7.6	27.7	0.7	1.9	4.4	b.d	0.6	55.7	100.1
RDL 904 3	0.6	0.6	6.8	24.5	0.6	2.0	1.8	0.3	b.d	63.7	100.9

Table 49, RDL composition

	1150°C	1200°C	1250°C	1300°C	1350°C
RDL 602 2	13.74	9.8	7.16	5.34	4.06
RDL 904 1	31.56	21.29	14.75	10.47	7.6
RDL 904 3	31.74	21.52	14.98	10.69	7.79
RDL 610 1	42.06	27.84	18.95	13.23	9.46
RDL 719 2	41.43	27.49	18.75	13.13	9.4
RDL 602 1	29.24	19.74	13.69	9.73	7.07

Table 50, RDL viscosity (Poise)

	RII
RDL 602 2	0.52
RDL 904 1	1.17
RDL 904 3	0.85
RDL 610 1	1.19
RDL 719 2	1.17
RDL 602 1	0.92

Table 51, RDL RII (Green – less reducing, Red – More reducing)

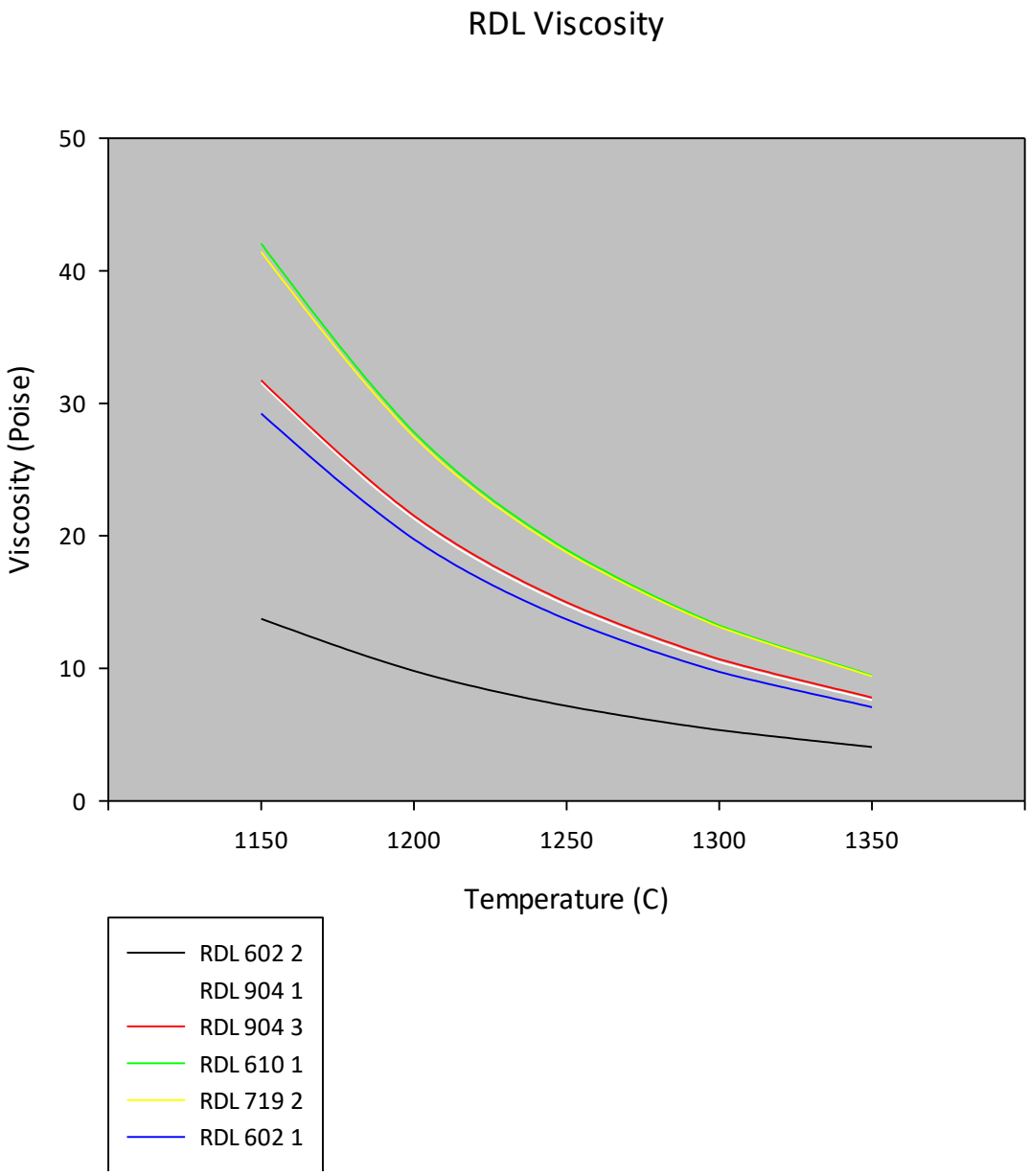

Figure 39, RDL viscosity (poise) vs temperature (°C)

4.3.4 Federal Mogul, Lydney (FML)

The slag was found in a limited archaeological investigation in features dating to the 2nd to 4th centuries AD using ceramic evidence. There were few other features discovered on this site so it would seem likely this was an isolated smelting site.

Macromorphology

The slag assemblage available from this site, consists of four types of slag; tap, tube, furnace and smelting slag. The tap slag has the typical ropey flow marks on the upper surface and smooth under surface. The slag tubes from this site have variation in size and also in shape, unlike other tubes the examples from this site are not round with oval and squared shapes present. There is a large slag tube which is clearly not an example of slag running through a tuyere once the airblast had ceased. Two of tubes have squared corners which indicate the shape of the void they filled were rounded on the upper surface and squared in the lower half. The furnace slag is in two forms, dense with few charcoal inclusions, and porous with charcoal inclusions. The denser slag would have been very fluid descending to the base of the furnace where there was little or no charcoal at the base of the furnace. The more porous and charcoal rich slag was formed by liquid slag descending through and flowing around charcoal fragments some of which were burnt out during the smelt creating voids. The furnace slag is very porous and light, the increased porosity suggests that the slag was liquid for a prolonged time which allowed for the gas trapped within the slag to agglomerate into bubbles. The assemblage from this site indicates that slag tapping furnaces were in operation at this site.

Plate 68, Slag tube with angled funnel end

Plate 69, Slag tube with angled funnel end

Micromorphology

The microstructure of the slag from this site is dominated by silicate laths and fine skeletal wüstite dendrites. There are some fine metallic prills present in the samples but the volume of these is inconsistent between samples. Some partially formed slag is present in one of the samples and one of the samples has fayalite laths which progress to blocky grains in the centre of the sample.

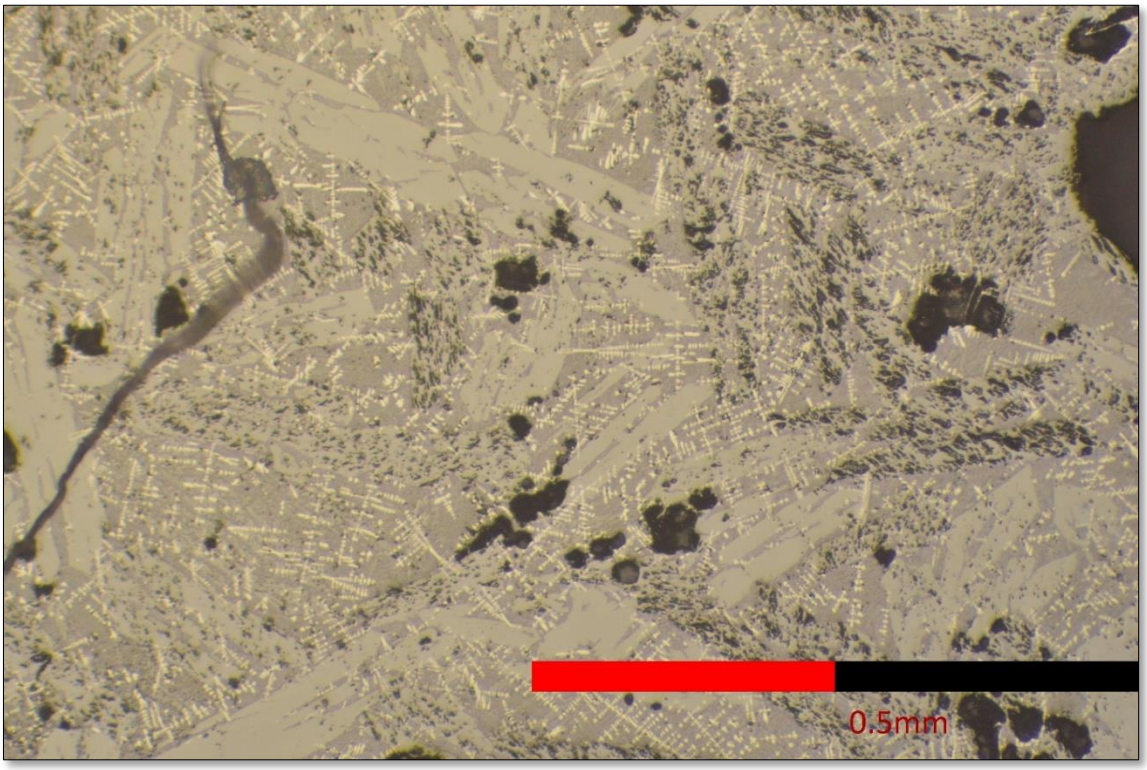

Plate 70, FML 3705 1 fayalite laths, skeletal wüstite

The slag from this site has a microstructure which suggests, from the form of the silicate and iron oxide dendrites, that the slag was cooled rapidly over a short thermal gradient. This would indicate that the slag was removed from the furnace. The only sample which does not show this is a subsample of the internal end of a slag tube. The presence of metallic prills in many of the samples shows that the slag properties were not conducive to all the metal formed during the smelt being agglomerated as one mass.

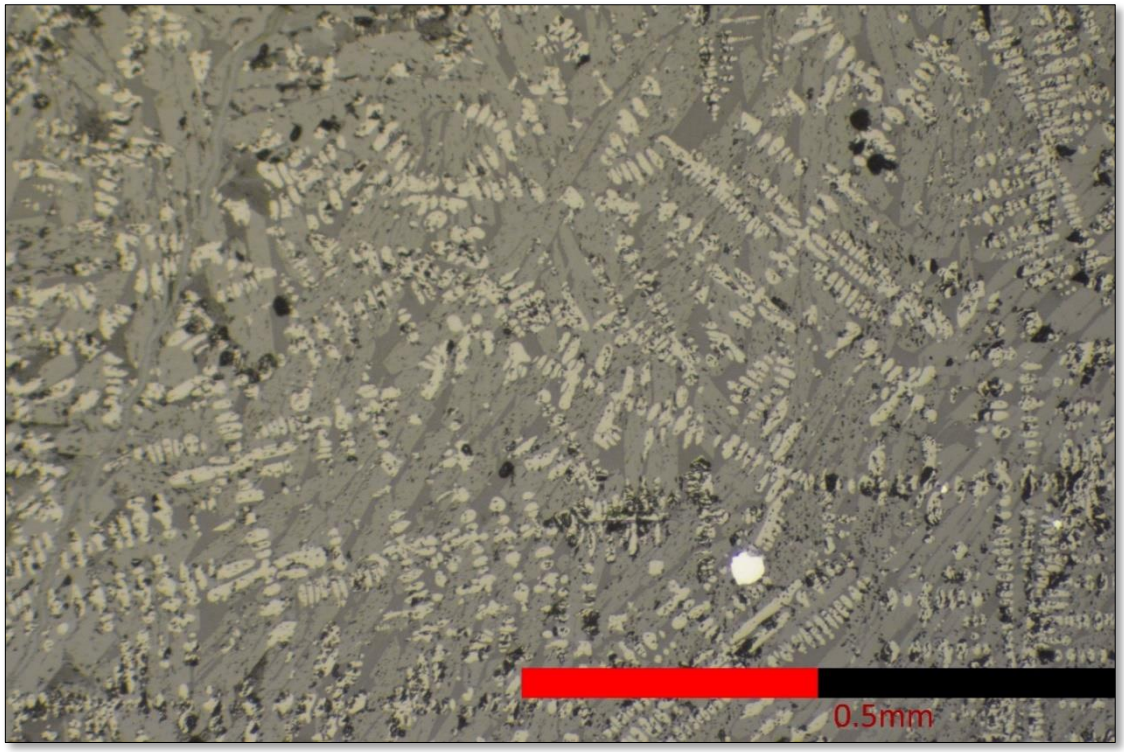

Plate 71, FML 4403 3, fine fayalite laths and globular metallic prill

The moderate levels of iron oxide, when present, suggests a process which was not completely effective at reducing the iron oxide of the ore to metallic iron. The slag viscosity is likely to be quite free flowing but depending on the chemical composition it may have needed to be heated above its liquidus temperature.

'Life History'

The macro and micro morphological results from this site indicate that the smelting that took place at this site was using slag tapping technology. The tap and tube slag from this site have rapidly cooled microstructure of silicate laths, the only sample which has a microstructure which has blocky fayalite is the internal end of a large slag tube. The compositional analysis of the tapped slag and slag tubes will be compared to examine whether there is a difference in the viscosity or liquidus temperature. If there was a difference would it be caused by changing conditions in the furnace or by the more liquid slag being tapped preferentially and more viscous slag solidifying as a tube.

Chemical Composition

The samples from this site all have a high level of iron oxide, FML 3705 2 is on the lower edge of the high iron oxide content. The alumina level of all the samples is elevated and correlates with increased calcium content as well, this indicates that the ore is the dominant contribution to the slag composition. The silica content of all the samples are within the normal range for bloomery smelting slag. As there is an elevated calcium content it allows for more of the iron to be reduced from the ore to metallic iron rather than fluxing the slag.

The liquidus temperature of the samples are all around 1150°C, the samples are split into two clusters, one close to optimum 2 (FML 4403 1 and 2) and one closer to optimum 1. The slag would not have been free flowing until approximately 1300°C. The same two clusters are seen in the RII which suggests two separate smelting events with different reduction conditions, one cluster (FML 4403 1 and 2) have less reducing conditions and the other cluster has more reducing conditions.

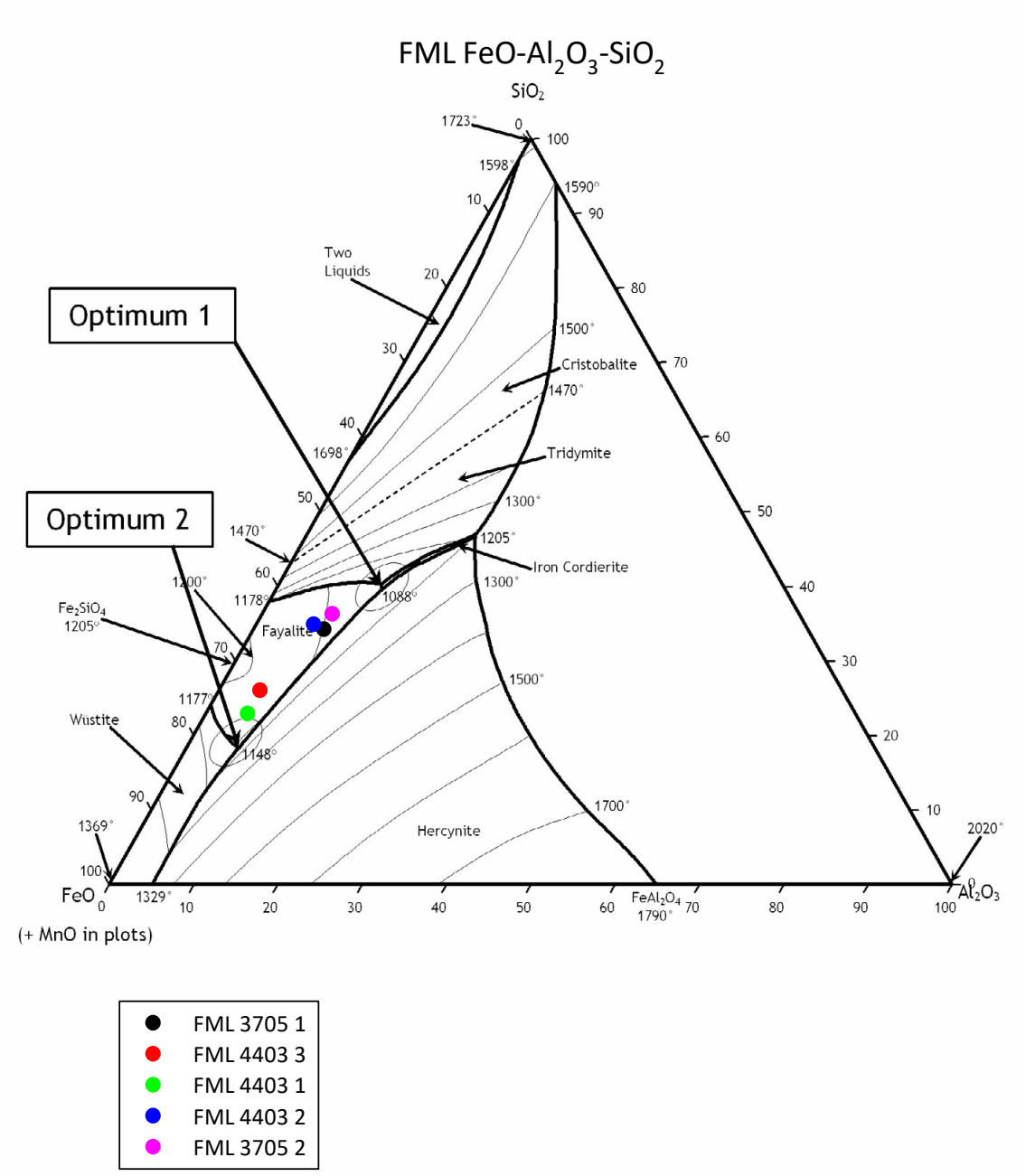

Figure 40, FML FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
FML 3705 1	0.3	2.1	7.6	30.4	0.5	2.4	4.7	0.3	0.2	51.6	100.2
FML 4403 3	b.d	1.0	4.8	24.6	0.6	1.4	1.6	b.d	b.d	66.4	100.5
FML 4403 1	0.9	1.8	4.9	21.7	0.8	1.1	1.5	b.d	0.4	69.1	102.1
FML 4403 2	b.d	2.0	6.5	32.3	0.9	1.7	2.9	0.6	0.4	54.3	101.6
FML 3705 2	0.5	1.7	7.4	31.5	1.0	2.6	6.7	0.4	b.d	48.8	100.6

Table 52, FML composition

	1150°C	1200°C	1250°C	1300°C	1350°C
FML 3705 1	48.28	31.61	21.39	14.86	10.57
FML 4403 3	26.55	18.25	12.81	9.2	6.76
FML 4403 1	26.93	18.63	13.21	9.59	7.1
FML 4403 2	49.39	32.56	22.09	15.38	10.96
FML 3705 2	44.17	28.98	19.56	13.56	9.62

Table 53, FML viscosity (Poise)

	RII
FML 3705 1	1.40
FML 4403 3	0.88
FML 4403 1	0.74
FML 4403 2	1.41
FML 3705 2	1.54

Table 54, FML RII (Green – less reducing, Red – more reducing)

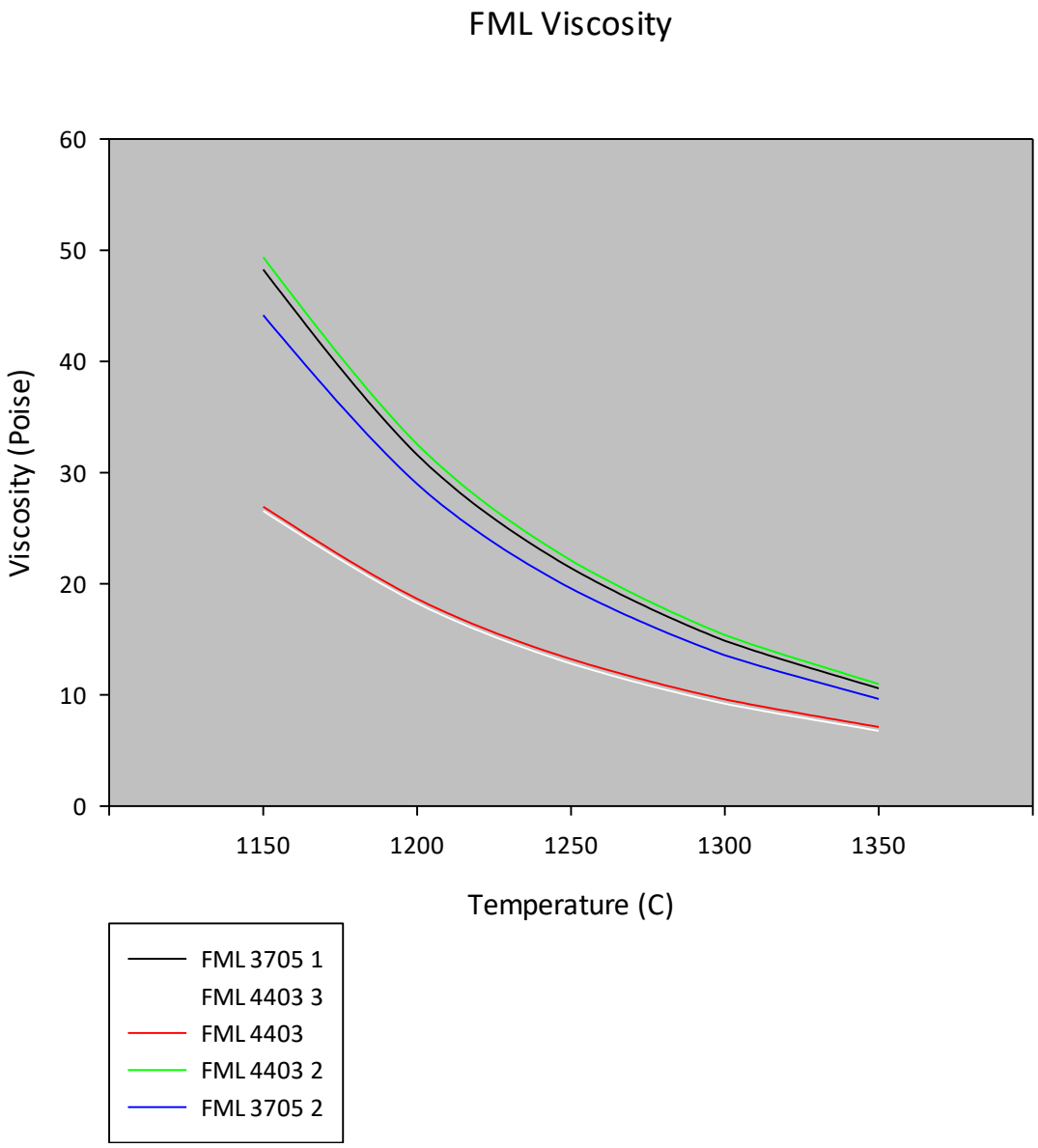

Figure 41, FML viscosity (Poise) vs temperature (°C)

4.3.5 Sherracombe Ford, Devon (SHF)

This specialist iron smelting site was in operation from the late 1st century AD until the middle 3rd century AD.

Macromorphology

The slag assemblage collected from the surface of this site is dominated by slag associated with a slag tapping furnace. Two main types were available to sample, tap and tube slag. The tap slag from this site has typical ropey flow marks on the upper surface with a smooth lower surface. The tube slag recovered from this site varies in diameter which agrees with the archaeological evidence from the site of a number of furnaces in operation. One of the slag tubes has evidence for funnelling at one end showing the internal end of a slag tube. As well as individual slag tubes there is also a stack of three slag tubes of similar diameters joined together. This assemblage is representative with the slag recovered from the excavations on this site.

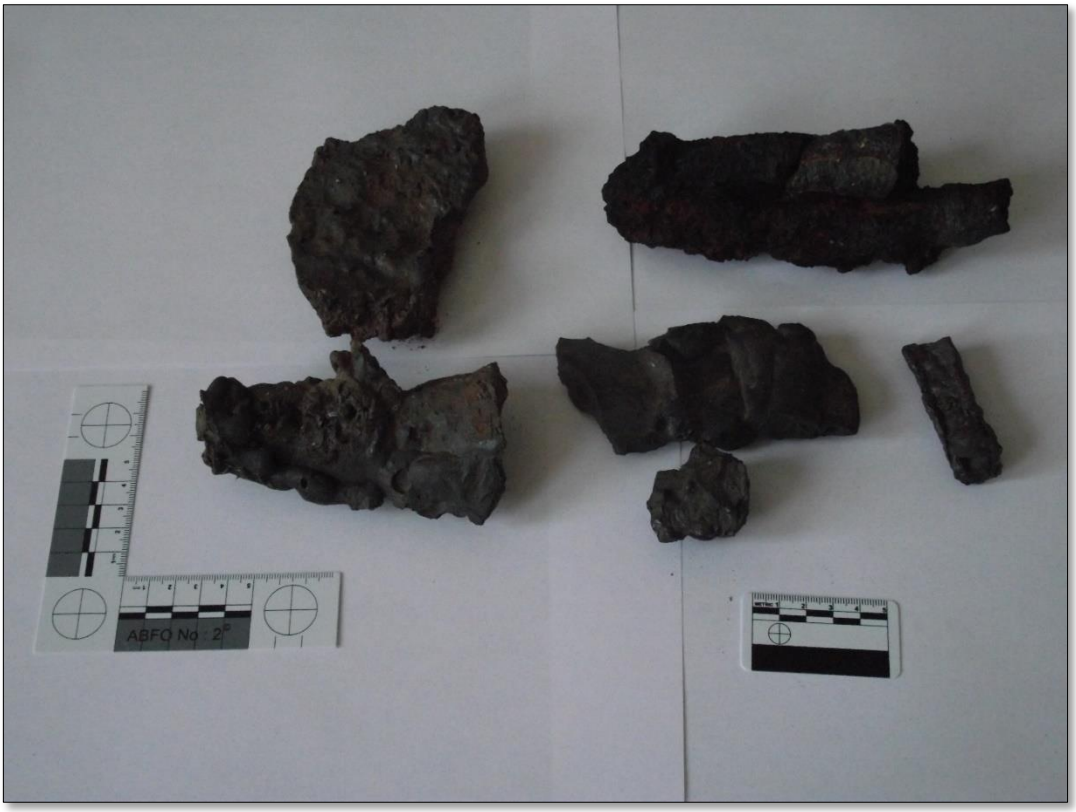

Plate 72, Sampled assemblage

Micromorphology

All of the samples from this site have fine silicate lath microstructure with variable wüstite content which while low in most samples is elevated in one.

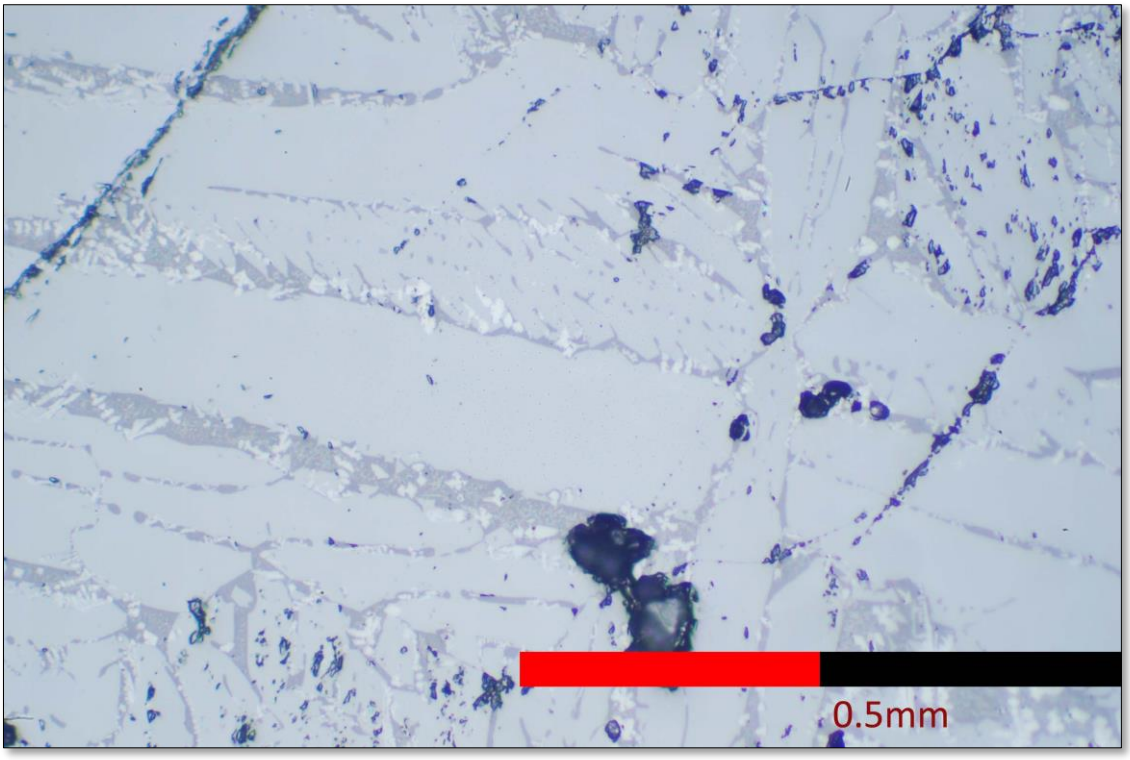

Plate 73, SHF 3.1, low wüstite

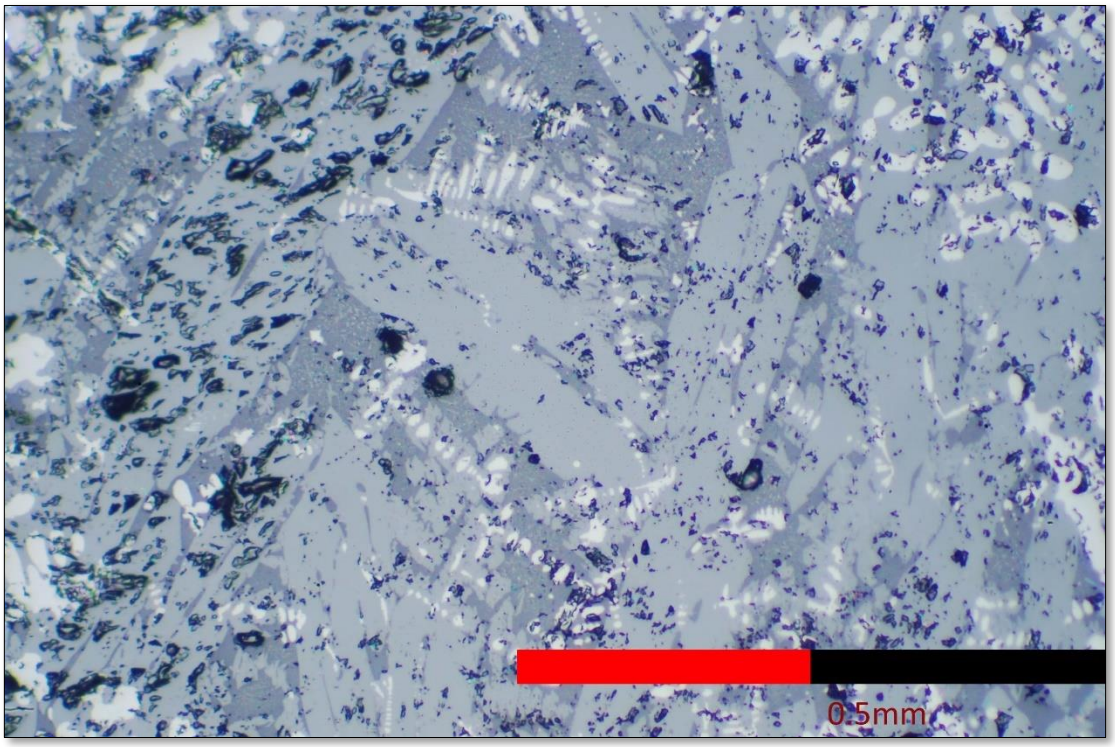

Plate 74, SHF 5.1, elevated wüstite

The fine silicate laths indicate the slag cooled rapidly over a short thermal gradient. This is supported by the wüstite dendrites being fine when present. This would suggest the slag cooled rapidly outside of the furnace. The low levels of wüstite within the majority of samples indicate high levels of reducing gases which would result in more iron being reduced from the ore and potentially higher carbon content in the metal. The reduced level of iron oxide would have increased the viscosity of the slag at or close to its liquidus temperature. As the fayalite and wüstite form indicates that the slag was tapped from the furnace the slag would have had to be fluid enough to be tapped out from the furnace and the temperature in the furnace would have had to be increased to ensure that it was.

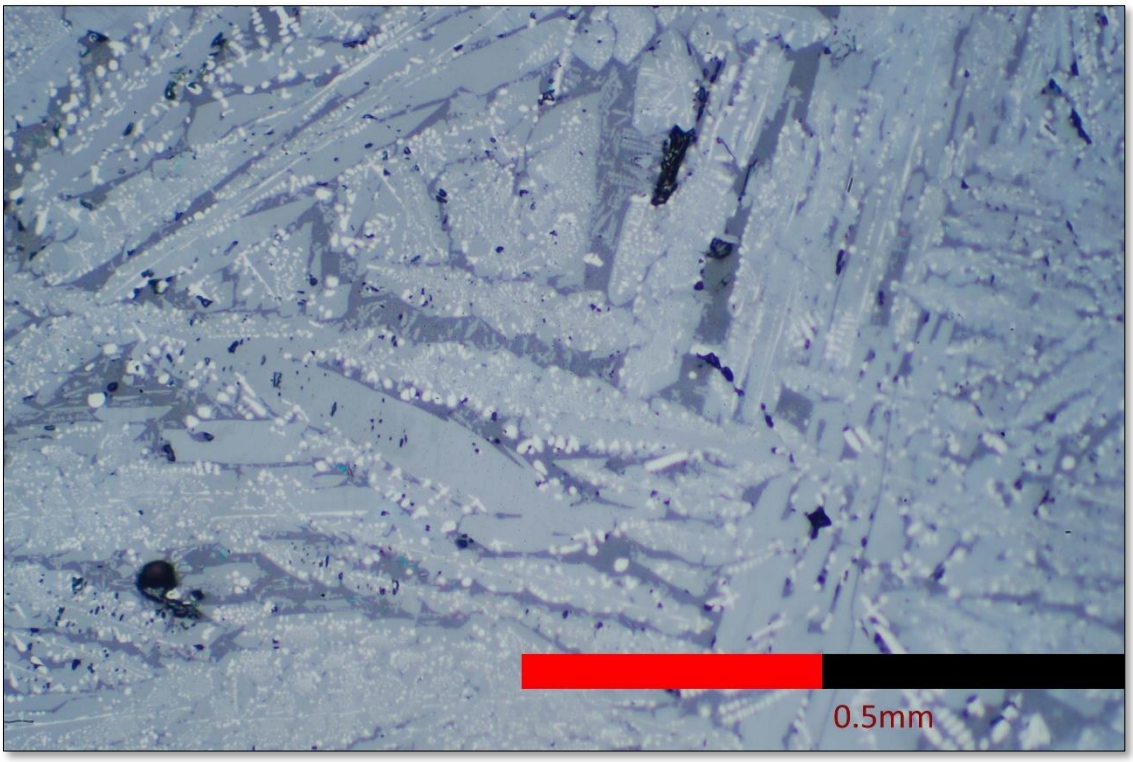

Plate 75, SHF 2.1, lath fayalite

'Life History'

The combined evidence from the macro and micromorphological indicates that the smelting process on this site used slag tapping furnaces which produced slag tubes as well as typical tap slag. The micromorphology of all the samples has a fine silicate lath

composition indicating that it cooled over a short thermal gradient. The tap and tube slag will both have had to be fully liquid to be removed from the furnace, the chemical composition will be used to estimate the liquidus temperature and the viscosity to examine the liquidity. Also how much iron oxide is being used as a flux and therefore how much iron was sacrificed to the slag. There is substantial difference in the amount of free iron oxide the effect this has on the viscosity of the slag has a direct effect on how high a temperature the furnace would have had to operate.

Chemical composition

The iron oxide levels of the slag from this site are at the higher end but still within the expected range of European bloomery smelting slag. Two of the samples have significantly less iron oxide; SHF 1.1 and SHF 4.1, of these SHF 4.1 has a much higher level of Manganese. This is much higher than would normally be expected. The alumina levels are elevated in the samples and the calcium levels are low. There is no correlation between changes in the amount either of these elements suggesting that the increases in alumina are related to increased contribution from the furnace lining. The silica levels are within the expected range but sample SHF 1.1 has an elevated level of silica. This combined with the lower level of iron oxide indicates a more reducing atmosphere in the furnace that produced this slag. This would have reduced more iron from the ore and potentially produced metallic iron which had a higher carbon content.

The liquidus temperature of the slag from this site ranges from 1125°C to 1175°C, the difference is mainly determined by the iron oxide content. The sample with low iron content (SHF 1.1) plots close to the optimum 1 region and the sample with the highest iron content plots within the optimum 2 region. Samples SHF 1.1 and 4.1 have a higher viscosity and would not have been free flowing at 1350°C. The other samples analysed would have been free flowing at 1300°C. The RII of this sites samples indicates that the

smelting carried out on this site was mostly more reducing but there are some samples which are less reducing.

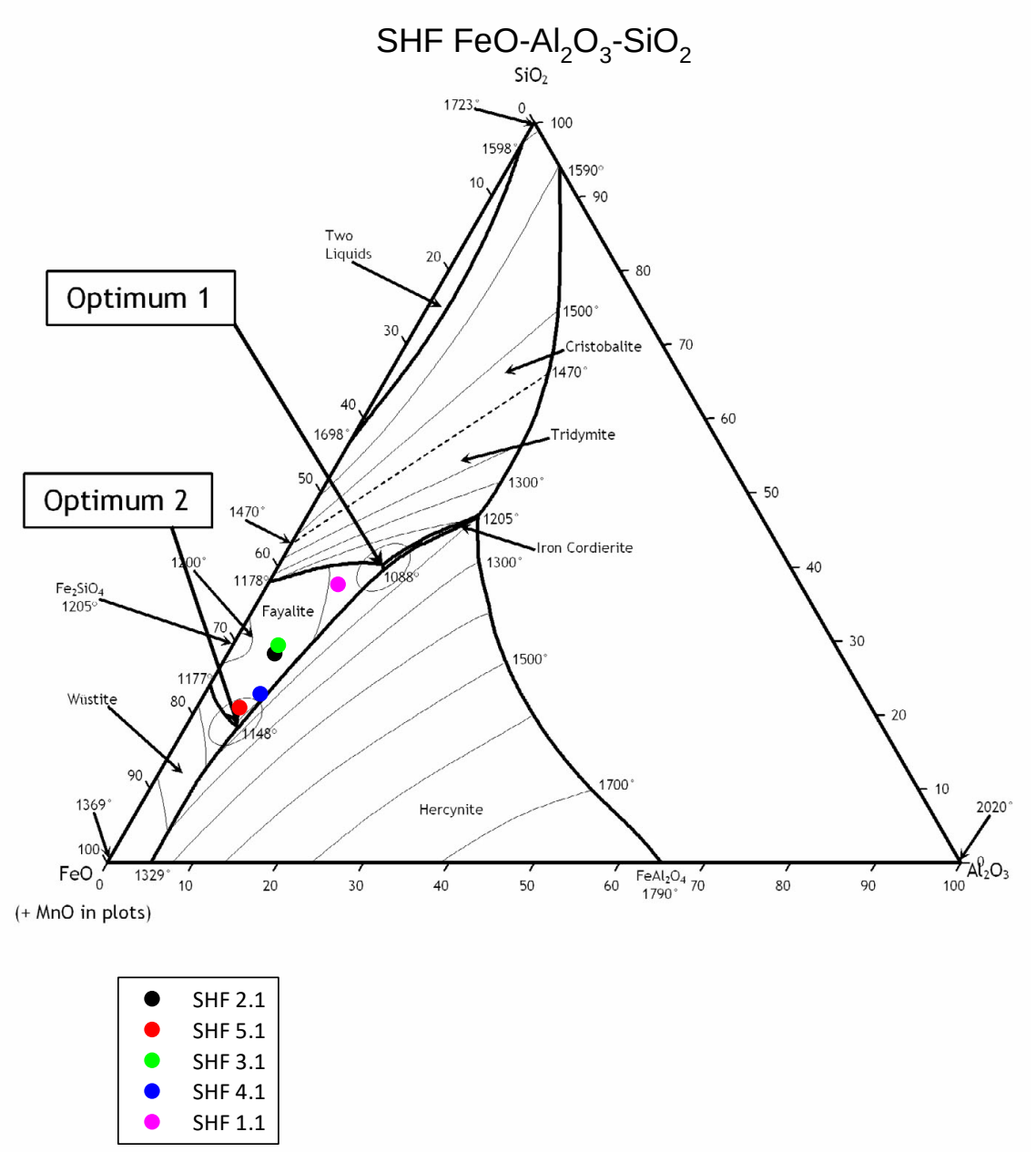

Figure 42, SHF FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
SHF 1.1	0.5	0.4	8.1	36.3	0.6	1.1	0.7	0.3	1.0	51.9	101.0
SHF 2.1	0.5	0.2	5.5	27.2	0.4	1.3	0.8	0.3	0.3	64.6	100.9
SHF 3.1	b.d	0.3	5.4	28.5	0.6	0.8	0.4	0.2	0.4	63.8	100.5
SHF 4.1	0.8	b.d	6.5	22.0	0.9	1.0	0.3	b.d	14.9	54.5	100.9
SHF 5.1	0.4	0.4	5.0	20.1	0.8	0.6	0.6	0.3	3.0	69.6	100.7

Table 55, SHF composition

	1150°C	1200°C	1250°C	1300°C	1350°C
SHF 2.1	30.5	20.56	14.25	10.11	7.34
SHF 5.1	46.79	32.4	23.01	16.72	12.4
SHF 3.1	43.43	29.15	20.1	14.21	10.27
SHF 4.1	75.14	51.15	35.76	25.6	18.72
SHF 1.1	97.78	62.14	40.73	27.45	18.98

Table 56, SHF viscosity (Poise)

	RII
SHF 2.1	1.00
SHF 5.1	0.66
SHF 3.1	1.06
SHF 4.1	0.76
SHF 1.1	1.64

Table 57, SHF RII (Green – less reducing, Red – More reducing)

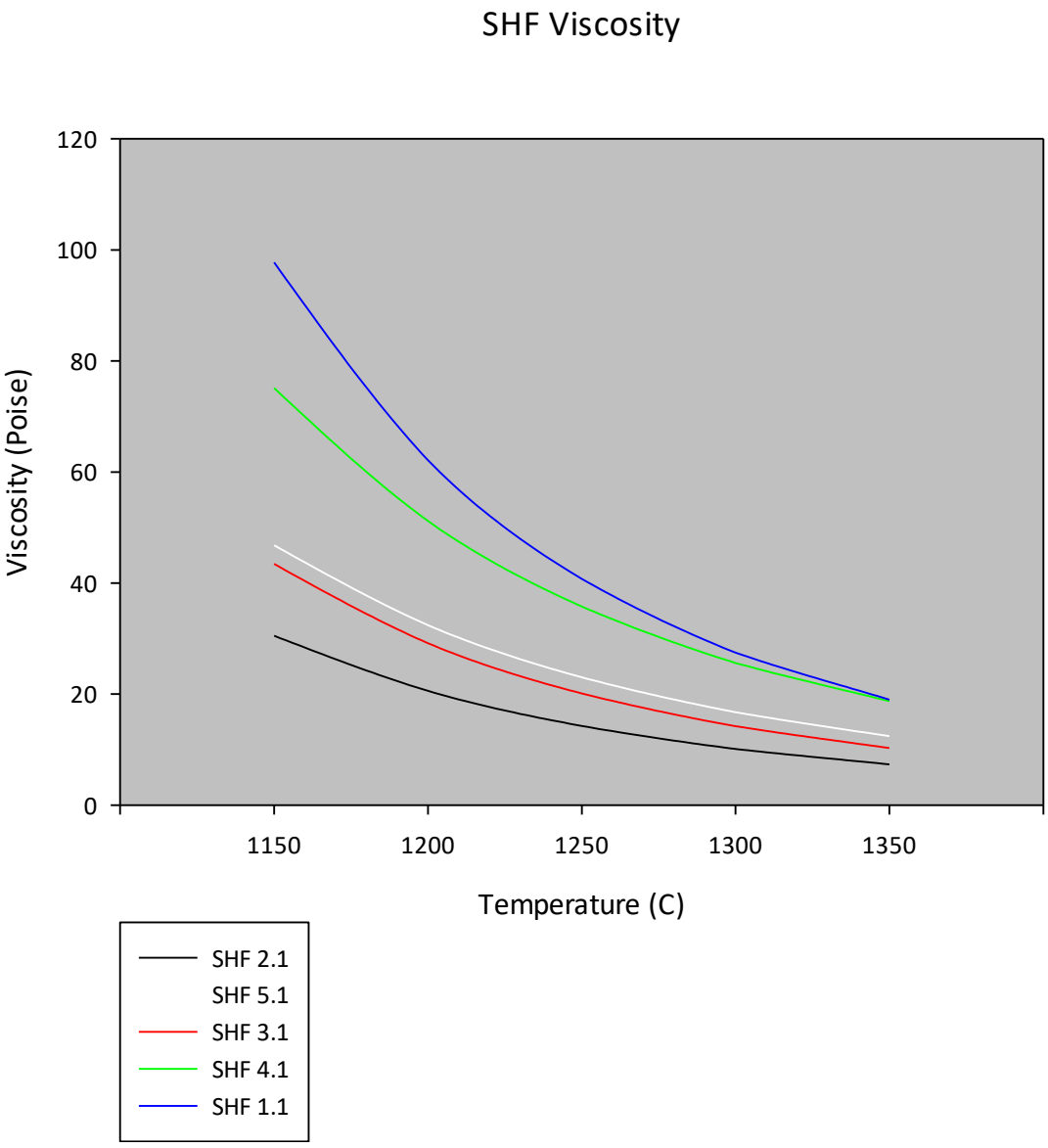

Figure 43, SHF viscosity (poise) vs temperature (°C)

4.3.6 Bradenham Fields Bloomery, Bloomery (BRAD)

This single furnace was dated to the early Roman period, it is remarkably well preserved structure as it was constructed into the side of a pit excavated into the side of a hill. The slag assemblage was recovered from within this pit which suggests that most of the assemblage was preserved.

Macromorphology

The slag from this site is typical of what would be expected from a slag tapping furnace. The assemblage consists mainly of tap slag, as well as small fragments of ropey flow marked slag there are larger pieces with evidence for higher liquidity. The upper surface of these pieces are very smooth indicating the high level of liquidity. These fragments are very similar to fragments found in situ at the base of the furnace and immediately outside the tapping arch. These with the furnace linings show that the furnace was reused at least twice.

Plate 76, Basal tap slag

Plate 77, 'Typical' tap slag

Micromorphology

The microstructure of the slag from this site is dominated by fayalite in lath and blocky lath form, most of the samples have a low level of wüstite with a small number having moderate levels.

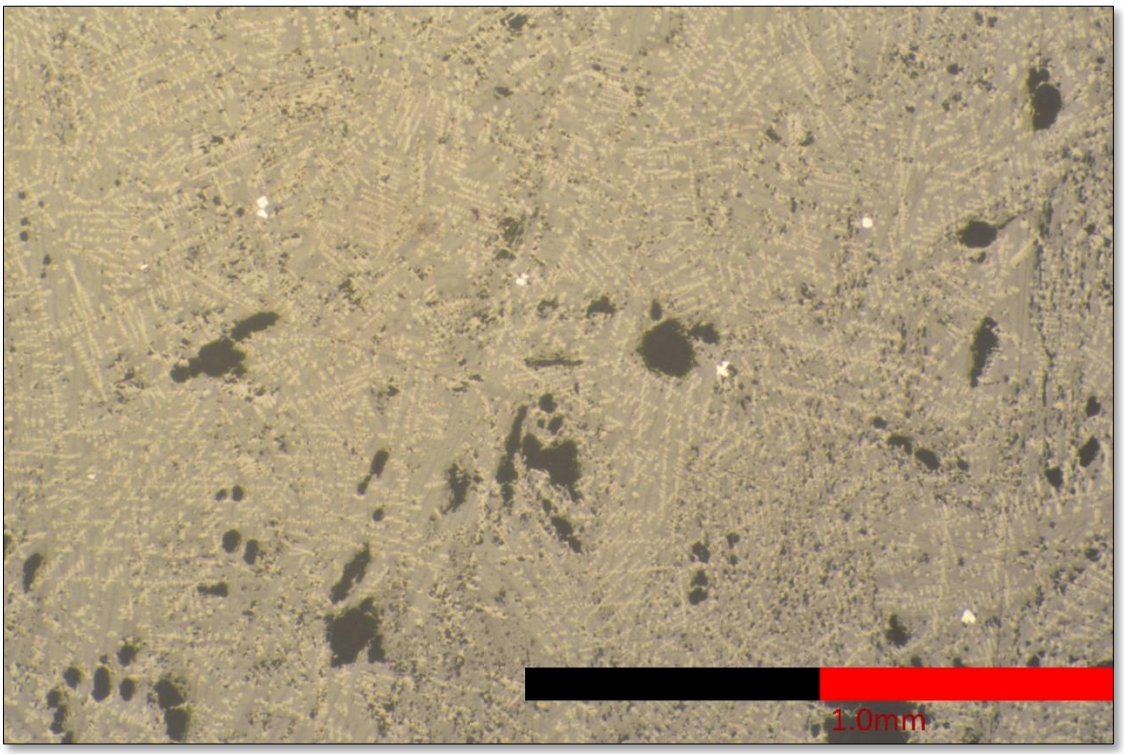

Plate 78, BRAD 1007 3 moderate fine wüstite dendrites and metallic prills

The lath fayalite indicates that the slag cooled over rapidly over a short thermal gradient. As the wüstite dendrites are fine and skeletal in most cases this supports the evidence of rapid cooling from the fayalite. This rapid cooling confirms the macromorphology that the slag was removed from the furnace. The relatively low levels of iron oxide suggest a process which was quite efficient at reducing the ore to metallic iron. The high levels of reducing gases would have had the potential effect of increasing the carbon content of the iron. The removal of the iron oxide from the slag to form more metal increases the viscosity of the slag which would then need to be heated beyond its liquidus to be able to flow from the furnace.

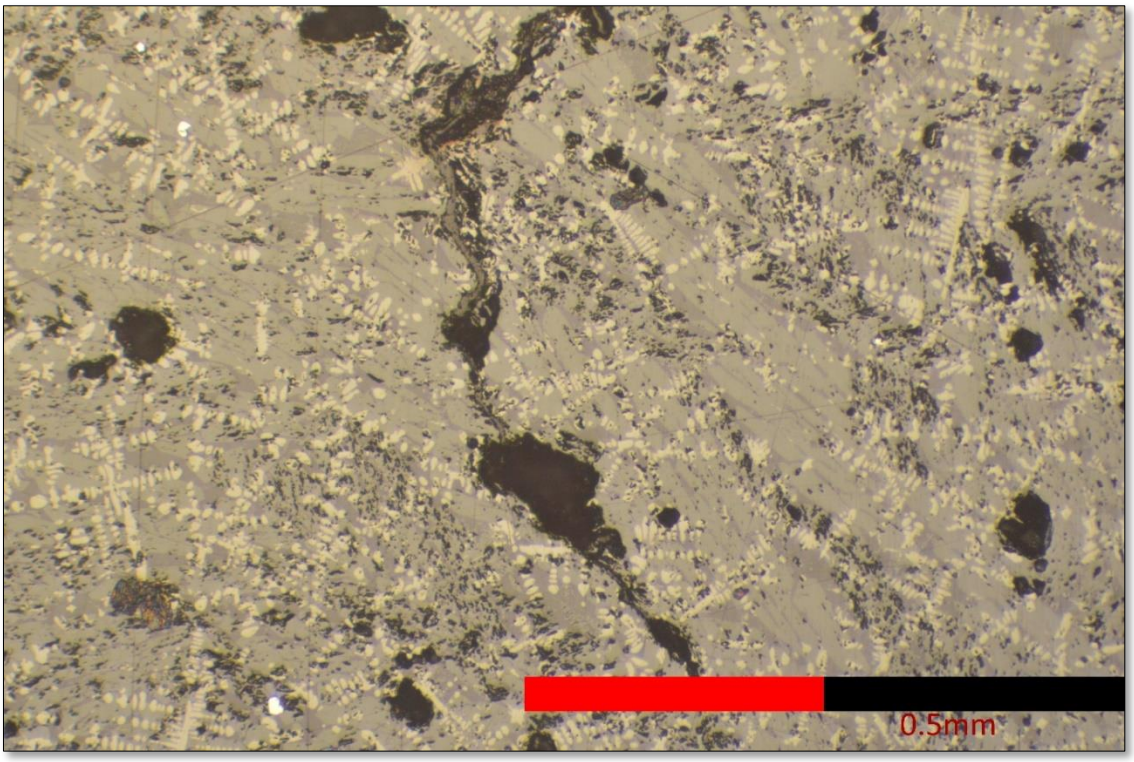

Plate 79, BRAD 1007 6, blocky fayalite laths

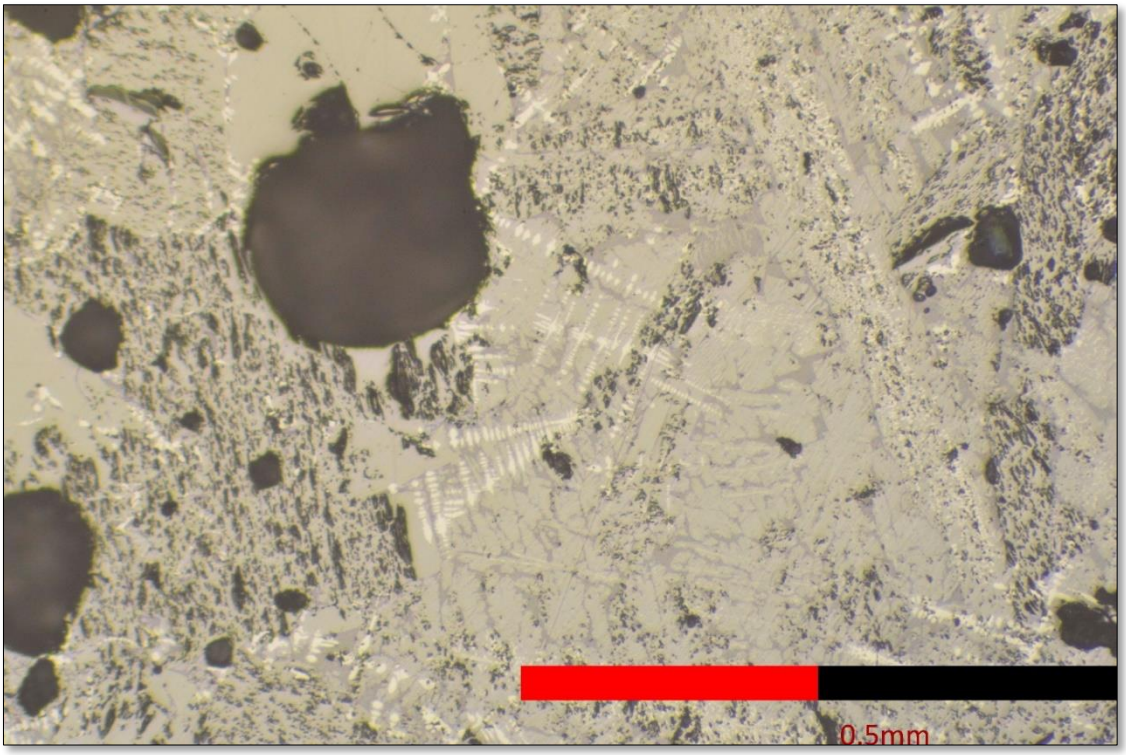

Plate 80, BRAD 1018 3, low wüstite levels

'Life History'

The macro and micro morphology of the slag from this site indicate a single slag tapping furnace was in operation on this site using the same or very similar methods between smelts. As there is slag from during and the end of the smelt comparing the composition between these will determine whether the inputs and operation of the furnace changed with determined end point of the smelt or the smelt ended while the furnace was still being charged with ore and fuel. The low levels of free iron oxide present in these samples would make the slag more viscous, the chemical analysis will show the liquidus temperature and the viscosity. This site is located away from conventionally exploited ore bodies so the chemical analysis will also be used to try and determine what ore source was used at this site.

Chemical Composition

The samples from this site are very consistent with the largest variation in any one element being only 2%. This suggests a very controlled process both in terms of technique and inputs. The iron level is consistently high around 66%. The phosphorus and calcium levels are both low while the alumina level is elevated suggesting inputs from the furnace lining.

The liquidus temperature of the slag has been estimated to be 1175°C and plotting very closely together. The slag would have become free flowing around 1200°C, sample BRAD 1007 7 would have been free flowing at a lower temperature but this is not due to differences in any one element but minor variations across several. The RII of the slag from this site shows that the smelt had slightly depleted reducing conditions but still was producing a reasonable amount of metal from the ore.

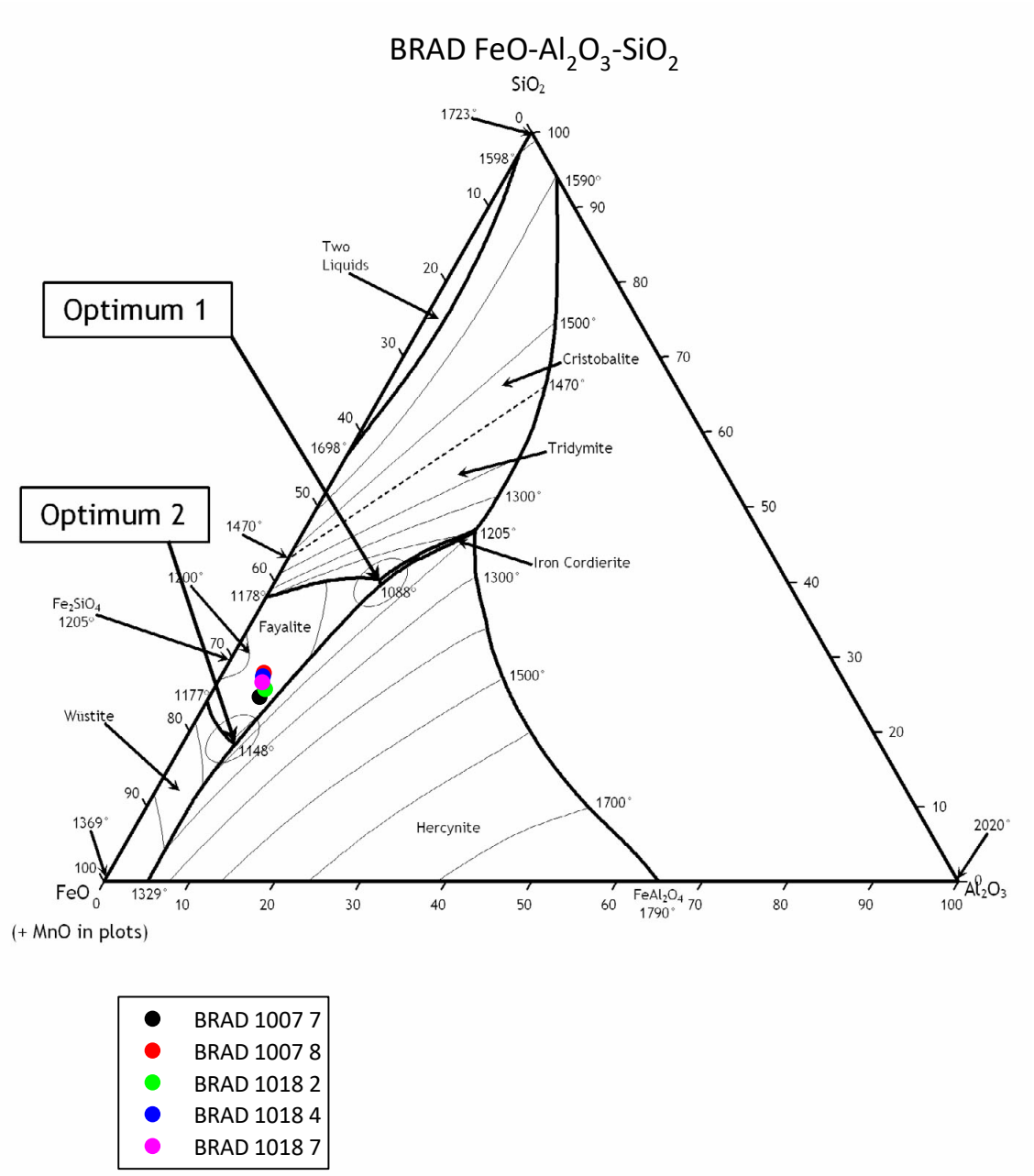

Figure 44, BRAD FeO-Al_2O_3-SiO_2 plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
BRAD 1007 7	b.d	0.4	5.5	23.3	0.7	1.1	1.7	0.3	0.3	67.4	100.7
BRAD 1007 8	b.d	0.4	4.5	26.8	0.6	0.5	0.9	b.d	0.6	66.1	100.3
BRAD 1018 2	0.4	0.4	5.6	24.4	0.8	1.0	1.5	0.3	0.8	65.7	100.9
BRAD 1018 4	b.d	0.4	4.6	26.4	0.6	0.5	0.9	b.d	0.5	66.4	100.3
BRAD 1018 7	0.5	0.4	4.9	25.5	0.7	0.7	1.1	b.d	0.6	66.5	100.7

Table 58, BRAD composition

	1150°C	1200°C	1250°C	1300°C	1350°C
BRAD 1007 7	24.95	16.96	11.9	8.54	6.27
BRAD 1007 8	33.99	23.09	16.11	11.51	8.4
BRAD 1018 2	32.51	22.02	15.38	11	8.04
BRAD 1018 4	32.96	22.93	16.01	11.45	8.37
BRAD 1018 7	31.84	21.72	15.18	10.86	7.95

Table 59, BRAD viscosity (Poise)

	RII
BRAD 1007 7	0.82
BRAD 1007 8	0.96
BRAD 1018 2	0.87
BRAD 1018 4	0.94
BRAD 1018 7	0.91

Table 60, BRAD RII (Green – less reducing, red - more reducing)

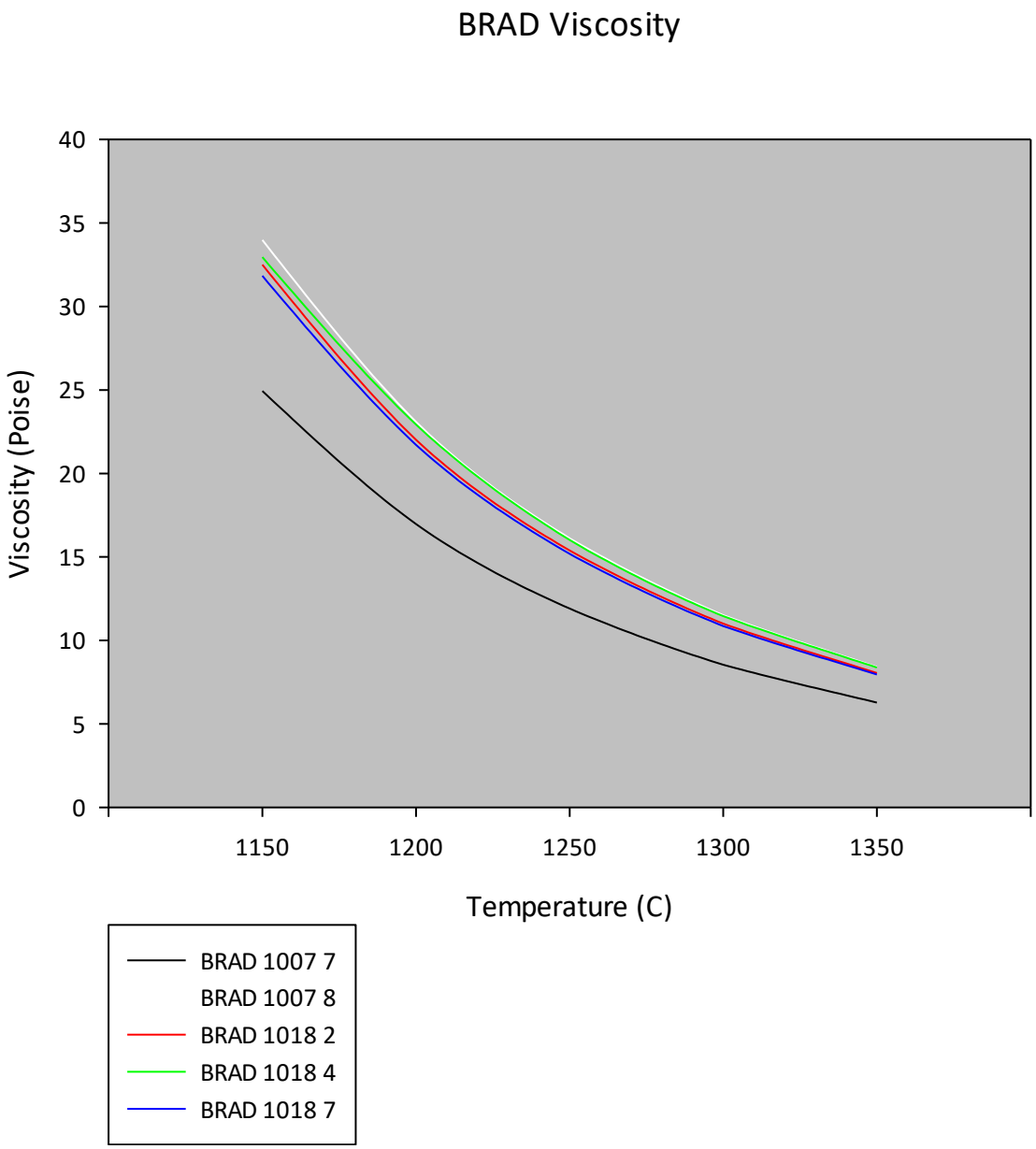

Figure 45, BRAD viscosity (Poise) vs temperature (°C)

4.3.7 Clearwell Quarry Extension, Lydney (CQS 15)

This site was uncovered during an archaeological evaluation in advance of stone quarrying, a single trench provided evidence for smelting associated with pottery from the 2nd century AD. It is likely that this is a small site given that slag was only found in one trench in a wider survey, it is not possible to suggest how the smelting activity fits into the immediate archaeological landscape until further excavation takes place.

Macromorphology

The assemblage of slag from this site consists of furnace slag, flow slag and tap slag. The most common form of slag from this site is furnace slag, several of these fragments have impressions of wood or charcoal in the surface. The diameter of these (c.15mm) would indicate a furnace of approximately 225mm in diameter if a single tuyere was being employed. A small quantity of flow slag was recovered which has evidence of flow one more than one surface, this material would have descended within the furnace and solidified outside the highest temperature area of the furnace. There was a very small amount of tap slag recovered from this site with the pieces being quite short suggesting they have been broken up. The assemblage suggests that this site was operating a non tapping furnace or a furnace which very little slag was tapped from.

Plate 81, Tapped slag

Plate 82, Smelting slag

Micromorphology

Microstructure of the slag across this site is dominated by silicate laths ranging from blocky to fine laths. Frequent iron oxide dendrites both fine skeletal and large globular forms. There are also fragments of unreduced or partially reduced ore incorporated into the slag.

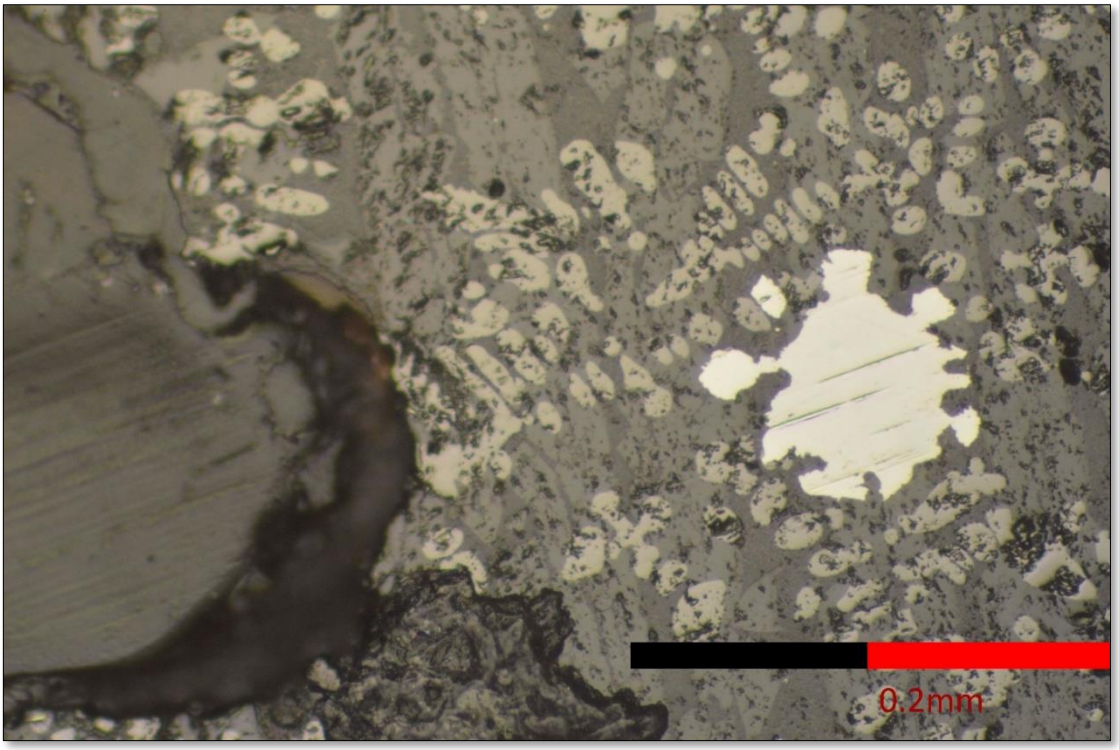

Plate 83, CQS 15 88 5, globular wüstite dendrites, 'splat' prill

The slag from this site is dominated by silicate laths which suggest that the slag was cooled rapidly over a short thermal gradient, by removal from the furnace. The relatively high levels of iron oxide present in the slag indicate that the process was not very efficient at reducing iron oxide to metallic iron. The higher levels of iron oxide in this slag would make the slag free flowing close to its liquidus temperature, the furnace would not need to operate too far above this temperature.

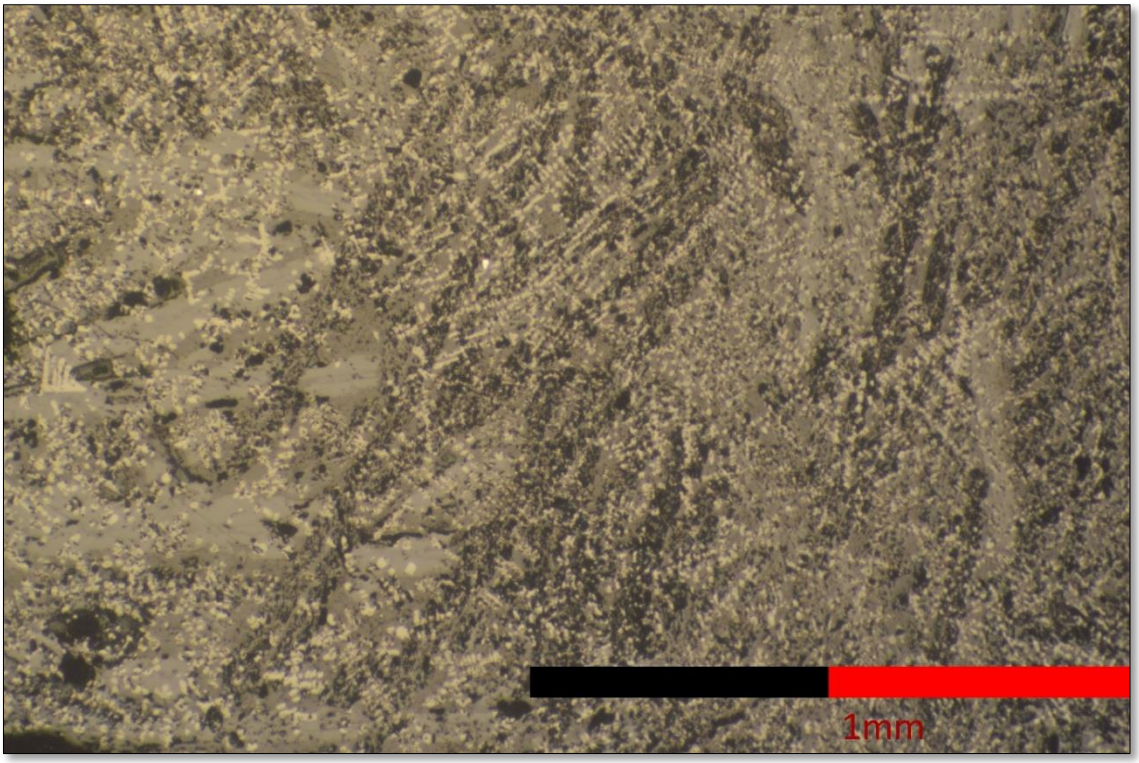

Plate 84, CQS 15 88 1, fayalite laths, fine globular wüstite dendrites

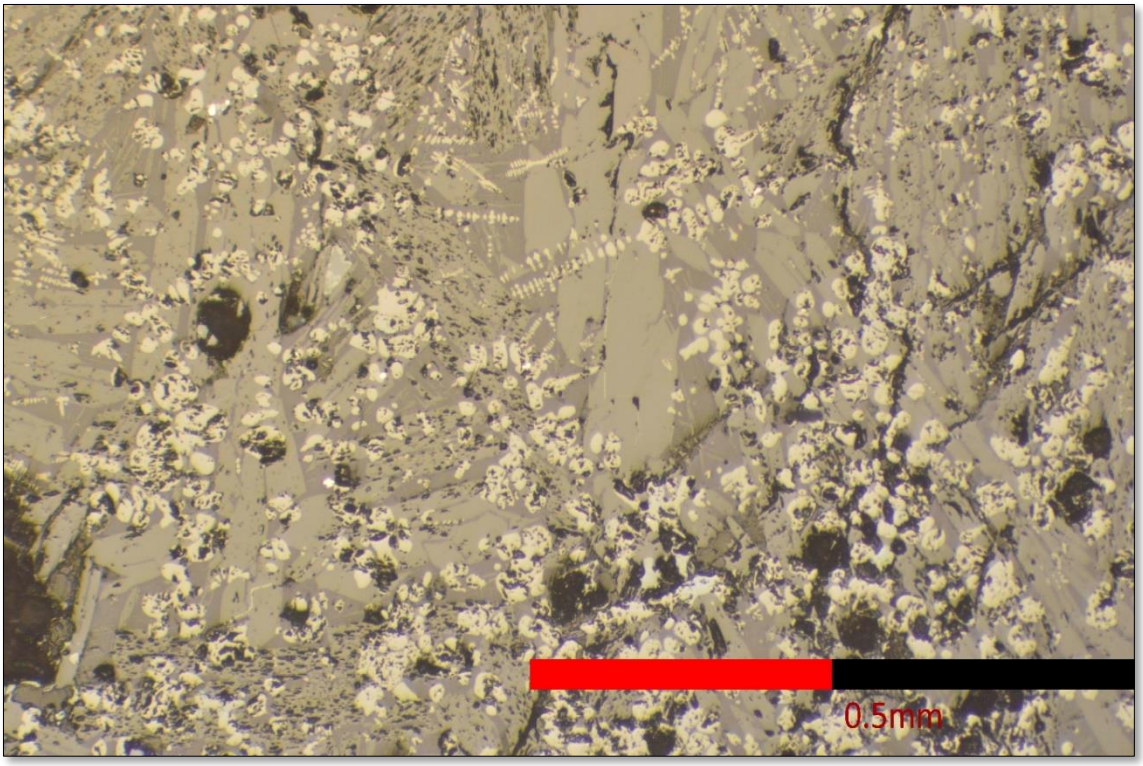

Plate 85, CQS 15 88 3, blocky lath fayalite

'Life History'

The macro and micro morphology when combined suggests that this site was employing a intermediate technology between tapping and non tapping methods. The macromorphology suggests that much of the slag was retained within the furnace, however the micromorphology indicates the slag cooled rapidly as if it had been removed from the furnace. The tapped and flow slag both have microstructures with fine fayalite laths indicating that they cooled rapidly. The chemical analysis of these samples will target the liquidus temperature and viscosity of the slag to determine whether the slag properties were especially suited to producing a free flowing slag and accidental tap slag.

Chemical Composition

The samples from this site all have high iron oxide content with one (CQS 15 87 4) having iron oxide above the usual range for European bloomery smelting slag (Pleiner 2000, 252). The phosphorus level is low suggesting a process which did not use a phosphorus rich ore and therefore produced phosphorus free iron. The alumina content is elevated in all the samples but it does not directly compare to the variation in the calcium content which suggests that the alumina content of the slag is a result of interaction with the furnace lining rather than variation of ore. The silica levels are consistent across four of the samples, only being slightly less in CQS 15 87 4.

The liquidus temperature of the slag from this site is split into two groups, CQS 15 87 4 has a melting temperature of around 1150°C very close to optimum 2. The remaining samples are clustered together with a melting temperature of 1175°C. The RII for the samples from this site show that the reducing conditions were both more and less reducing but mostly less reducing with the more reduced samples being close to the composition of fayalite (Table 67). The viscosity of the slag from this site indicates that the slag would not have been free flowing below around 1300°C (Table 68). Sample CQS 15 87 4 has the

lowest viscosity, being free flowing at 1200°C, close to its liquidus temperature. However this slag also has the lowest RII suggesting it was formed during a smelt with the lowest reducing conditions suggesting it was the least effective at producing metallic iron.

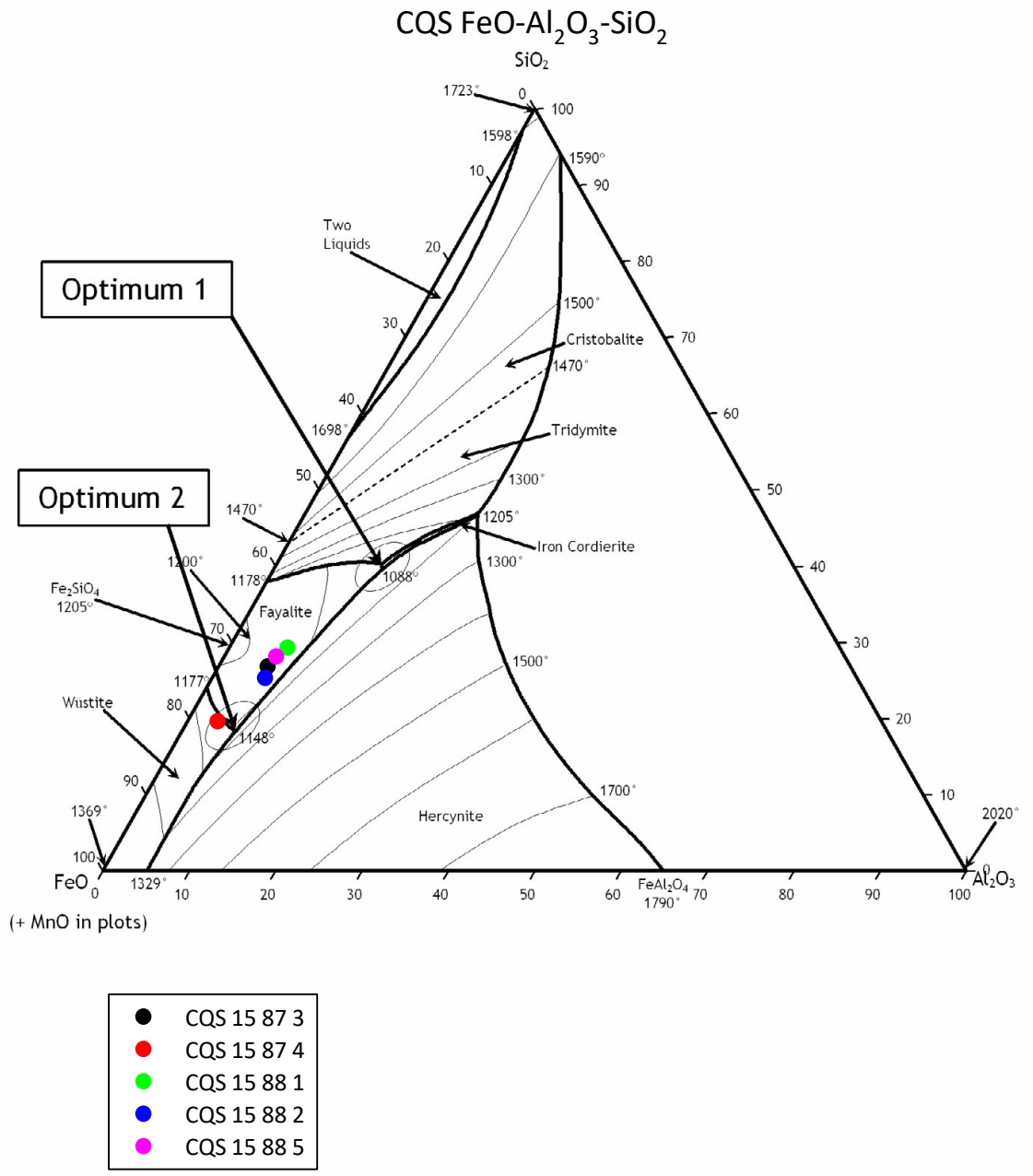

Figure 46, CQS FeO-Al₂O₃-SiO₂ plot

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
CQS 15 87 3	0.4	1.5	5.8	25.2	0.5	1.6	2.8	0.3	0.3	62.7	101.0
CQS 15 87 4	b.d	1.3	3.8	18.9	b.d	1.1	1.5	b.d	0.4	73.3	100.4
CQS 15 88 1	b.d	1.8	6.6	26.8	0.9	1.7	4.8	b.d	b.d	58.2	100.8
CQS 15 88 2	b.d	1.3	6.4	24.5	b.d	1.0	1.1	b.d	b.d	66.0	100.2
CQS 15 88 5	b.d	1.6	5.9	25.7	0.7	1.8	4.6	0.4	0.4	59.5	100.6

Table 61, CQS composition

	1150°C	1200°C	1250°C	1300°C	1350°C
CQS 15 87 3	29.98	20.36	14.19	10.14	7.4
CQS 15 87 4	19.96	13.99	10.07	7.4	5.5
CQS 15 88 1	32.36	21.69	14.96	10.58	7.65
CQS 15 88 2	36.63	24.88	17.31	12.33	8.98
CQS 15 88 5	28.81	19.63	13.65	9.72	7.07

Table 62, CQS viscosity (Poise)

	RII
CQS 15 87 3	0.96
CQS 15 87 4	0.61
CQS 15 88 1	1.10
CQS 15 88 2	0.89
CQS 15 88 5	1.03

Table 63, CQS RII (Green – less reducing, Red- more reducing)

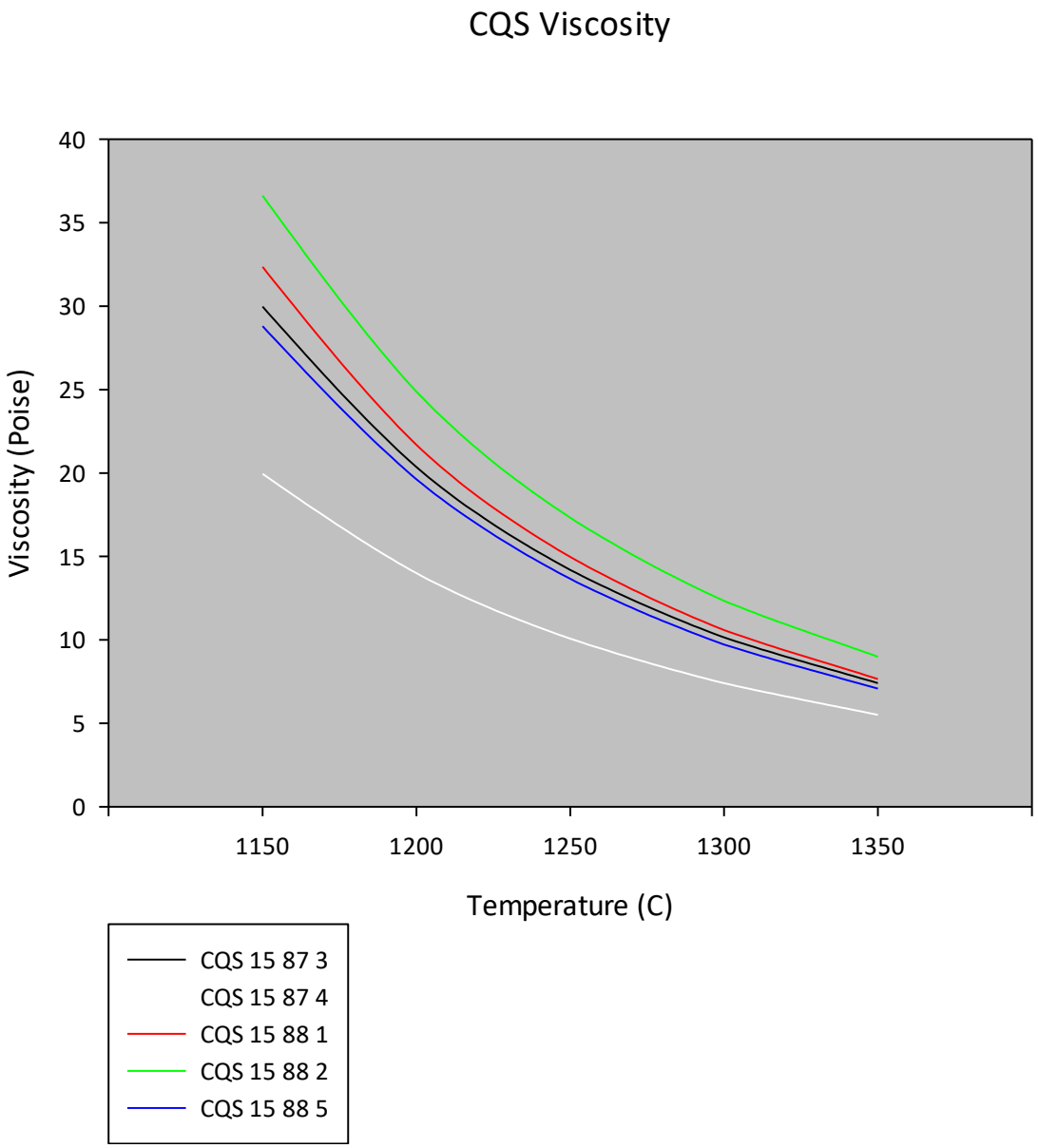

Figure 47, CQS viscosity (Poise) vs temperature (°C)

CHAPTER 5 – CONCLUSIONS

The objective of this research has been to examine the transition between the Iron Age and Roman periods in southern Britain through the production of iron. Closer integration of archaeometallurgy and archaeology has led to each becoming more relevant to each other. To examine ancient smelting processes the study of the waste material is the artefact type preferred here, furnaces survive poorly in the archaeological record and metal objects are a reflection of object production rather than the raw metal. The difference between the Iron Age and Roman periods in terms of the production of iron are both cultural and technical and will be discussed as such.

Discussions of ancient technology have been dogged by focus limited to the technical aspects and a refusal to extend these conclusions into the social aspect of the narrative (Pfaffenburger 1992). It is possible to situate the results shown in chapter 4 within the archaeological data without addressing this placement but it would leave this work as an isolated study difficult to integrate into wider studies of the Iron Age to Roman transition or either period individually. Therefore, the results reached above will be discussed briefly here with a regard for the archaeological background as defined in chapter 2.

How iron production differed between the Iron Age and Roman period in Southern Britain can be considered in two ways, firstly the technical differences of how the iron was produced over this time span and the recurring trends at the sites studied here as well as in the broader literature. Secondly, by interpreting these technical aspects to determine what social differences were reflected by them. The accuracy of the dating of iron smelting sites mean that only a coarse chronological difference has been possible to determine, meaning that it is only possible to *suggest* differences between the two periods rather than explain or describe how the change happened.

Following on from the work of Paynter (2006) and Young (2010a) it is possible to suggest that there was a preference for the exploitation of tertiary iron ore deposits or bog ores. This type of ore can be identified through slag containing elevated levels of phosphorus. Phosphorus partitions between the slag and the metal, therefore these sites would have produced phosphoric iron. The phosphorus affects the crystal structure of the iron, taking the place of carbon, therefore hindering the uptake of carbon and preventing the formation of steel. It also increases the hardness of the metal, this was considered to be a negative feature by archaeometallurgists, with the suggestion being that this was a less useful material than low carbon steel or even pure iron.

The sites dating to the Roman period examined here and in the literature do not appear to have used bog ores or geological sources which would have resulted in phosphoric iron. It is known from areas such as the Weald and the Forest of Dean that sub surface deposits were exploited through excavations of pockets or seams of ore. This would have meant that the metal produced could have freely absorbed carbon if the conditions were suitable during the smelt, therefore allowing for the production of steel, or if the absorption of carbon was even higher, cast iron would have been a possibility.

On this subject it is important to consider the type of metal being produced, the ore is a crucial factor for this as we have seen, but so too are the conditions in the furnace. These are to some extent recoverable through analysis of the slag. For those sites exploiting phosphorus rich ores it would not have been possible to produce iron which had a carbon content high enough to be quench hardened, an important and widely discussed development. Low carbon steels such these were present in the Iron Age and have been recovered from early Iron Age contexts. Those sites using other ores have greater reducing conditions, this indicates two factors, they could have been producing more iron from the ore, ‘more efficient’ and that they could have been producing iron with an elevated iron

content. Therefore, they could have produced steel suitable for edging tools and quench hardening. Large quantities of this type of iron would have been required not only for equipping the Roman military but also to provide the tools and equipment for the agriculture, industry and crafts that dominated the Roman economy.

How the slag was or was not removed from the furnace was a factor which would have affected a number of parameters during the smelt. During the Iron Age the more primitive non-slag tapping furnace was used, this type as described in chapter 2.1.4 and the references within, while the slag tapping furnace was introduced in the late Iron Age to transition period and became dominant in the Roman period. A further development observed at a number of sites through this study is the use of slag tubes. These changes, to use a modern term, made the smelting more *efficient*, e.g., the smelt could be carried out for longer in each individual furnace, creating a larger bloom. It not only allows for a change in product but requires slightly different conditions in the furnace and allows for the exploitation of less rich ores. This may be a partial explanation for the vast growth in the production of iron in places such as the Weald and the Forest of Dean during the Roman period. The adaptation which resulted in the production of slag tubes would have further increased the benefits of slag tapping. By removing slag through a small hole which the flow of liquid would have completely filled less heat and reducing gases would have been lost, keeping constant conditions in the furnace chamber.

These technical differences while the easiest to identify, would not have been the sole driving force as metallurgists would like to believe, but would have been the result of underlying socio-cultural factors. The exploitation of different ores reflects changes in the scale of social organisation between these two periods.

While different types of ore are used in both periods and there is likely to have been some overlap the scale of the deposits exploited between these two periods is the important difference. The deposits utilised in the Iron Age, while smaller were much more widely dispersed. The patchwork of communities across Britain in the Iron Age would have had direct access to sources of iron, or either through short distance travel for resource exploitation as suggested by Hill (2011, 262-3) or through trade. The concept of trading iron to areas unable to produce it could be interpreted as a trigger for the initiation of production of currency bars. It is likely however that currency bars are not solely the result of localised smelting of iron but part of more complex social and material cultural changes. Essentially a desire for metal with certain properties which would not be available locally. The transition to areas of concentrated larger deposits in the Roman period indicates the arrival of centralisation. This centralisation allowed for a centralisation of labour, infrastructure and trade networks used to drive and support smelting in certain locations suited to large scale production.

The Iron Age production of iron was intrinsically linked with the underlying belief system across Britain. Everyday life in the Iron Age can be considered to have been directly linked to the agricultural calendar. Using the yearly cycle laid out by (Fitzpatrick 1997) it is possible to project when each stage of raw material exploitation and preparation would have been carried out. It has been suggested that the smelting of iron would have also been carried out within this due to the availability of labour. It is true that the collection, preparation and transportation of raw materials would have needed a substantial amount of labour, the smelt itself has been shown to have required skilled smelters. This specialist skillset would have put the individual not only in a privileged situation, supported by and supporting any hierarchy or community (Hill 2011, 244). The same extended social structure which allowed the support of a non-food producing specialist could also have

been responsible for the trade and exchange network which would have distributed currency bars (Cunliffe 2005, 496-499).

The transition to the Roman period sees this connection of processes to an underlying belief system incorporated into the agricultural calendar ceasing and being replaced with a level of organisation which allowed for the production of iron to reach an industrial scale (Sim and Ridge 2002, 22). It became a truly year round production for an established market of domestic, industrial, agricultural and military consumers. As shown by the work of Sim and Ridge (2002, 22) up to 150,000 people were directly or indirectly occupied in the production of iron in Britain alone. While there appears to have been a large workforce involved in the production of iron the results above show that there was a concern about the most efficient utilisation of labour and fuel. That a single smelt carried out for a prolonged period was desired more than a series of smaller smelts using the same quantity of raw materials to produce the same amount of desired product.

The results and brief discussion above show that there were technical differences in the smelting of iron and that these were connected with broad differences in the social organisation of Britain in the Iron Age and Roman periods. But the real question is would it be possible to determine how did changes in iron production affected social and economic relationships.

One change to society caused by changes in the iron smelting process would have been the availability of iron. Communities no longer needed to produce their own iron, new techniques and the exploitation of dense areas of ore deposits made it more viable to purchase raw stock iron or finished objects rather than dedicate labour at specific times to collect and transform the raw materials into metal. This would lead to a reliance on others rather than self-sufficiency. An individual smelter would no longer be able to reinforce the

power of an individual or to strengthen the community as a whole. With the growing influence of Romanisation and increasingly ready access to greater trade markets the skill of the smelter could result in a growth in personal wealth and prestige.

The actual production of iron in the Iron Age differs from that often discussed in wide reaching works on the period. The concept of small, settlement based, 'cottage industry' (Cunliffe 2005, 493-499) production of iron can no longer be consistently applied. This is partially due to the greater number of smelting sites being excavated but also the nature of the sites excavated. Until the growth of rescue and developer led archaeology most Iron Age sites excavated were enclosed sites or settlements (Hill 1995, 58). Excavation of more sites not fitting these criteria has meant that more isolated smelting sites have been excavated. These have begun to fill the void between iron excavated and direct evidence for metal produced. The presence of more of these sites allows us to be more stringent with our criteria for iron smelting, no longer do we need to accept evidence with poor dating or context.

5.1 Iron Age

The traditional metallurgical view was that Iron Age iron production was by either low skilled or transient craftworkers (Salter and Ehrenreich, 1984). The discovery and examination of sites in East Yorkshire (Halkon and Millet 1999; Halkon and Starley 2011) and North Wales (Crew 1988; 1989; 1995) show that the sites were operating at a scale and complexity which suggest a specialised workforce producing iron for more than local consumption. The Berkshire-Hampshire-Surrey cluster of sites examined in detail here indicate that the North Yorkshire and North Wales clusters are not unique. The presence of these specialised areas of iron production does not preclude small scale single smelt events, but it suggests a complexity matching the complexity of Iron Age Britain itself.

There are two types of site studied as part of this thesis: specialist isolated iron smelting sites and smelting on settlement sites. There is an obvious difference in scale between these types, the isolated smelting sites are significantly larger and more frequently visited than the single smelting events at settlements. This difference can fit within several existing theories of social organisation during the Iron Age. It can be argued that specialist smelting sites are an example of a hierarchical society where a skilled workforce is supported by a leader in order to produce the material which can be used to further their power, or to produce a tradable commodity. It can also be argued that they are the result of a heterachical society where the wider community combines its resources to support those undertaking the smelt. It could have been possible that both were possible at different times and different places. The scale of these smelting events would have required significant planning, they would have also had to fit within the agricultural calendar (Fitzpatrick 1997). The smelting at Sindlesham, for example, would have required the collection of bog ore, during the summer when the wetlands would be at the driest, and the collection of wood and processing it into charcoal, best carried out in the winter. The winter has been suggested as the main time that smelting would have been carried out because of spare labour being available.

The evidence from smelting at settlements shows that both skilled and unskilled smelters were operating in this period. The evidence from the GRR samples is of a smelt that appears to have failed or been terminated early, as there is no other evidence on site for smelting and this single event was unsuccessful then it would appear to be evidence for an attempt by an unskilled smelter. While, in contrast the smelting at MGE was successful and it appears that more than one event may have taken place. Aside from illustrating that differing levels of skill were present within a geographical cluster this shows that there was

a general availability of metal or metal artefacts so that settlements did not have to produce their own metal.

As shown through ethnographic work in Africa and Asia traditional iron smelting is inextricably linked to ritual and taboo (Herbert 1993). This must have been true in the Iron Age, while there is limited evidence for this on smelting sites it is possible to find connections to the universal cosmology of Iron Age Britain. There is a palpable connection to agriculture and fertility, the impression of straw in the base of the large masses of slag from Sindlesham show a preparatory deposit placed at the base of the furnaces. Straw is the final product of the growing of grain, the useful by-product after the grain has been threshed from its stalks. The placement of this at the base of a furnace used to produce iron which could have made make the next generation of tools to till the land and harvest the crops is significant. This would be a direct connection allowing the successful production of crops to the following year. This can be also seen with the deposit of metalworking tools at Garton Slack in a pit of charred grain (Giles 2007b, 395; Brewster 1980, 363). While these have been interpreted as being a deposit in desperation to invoke powers for a successful harvest following a poor harvest (Giles 2007b, 402-403) the deposition of straw in a furnace may be to invoke a successful smelt or to carry a successful harvest to the following year, via the tools used to prepare the land and collect the grain. The presence of the impressions of wood in slag as seen in the samples from MFF could be similarly interpreted as imbuing the iron with power to become effective woodworking tools. The deposition of this material may have had a practical purpose in supporting the charge at the base of the furnace but the choice of this material, consumed by and incorporated into the iron would have had a significance beyond the merely practical. The practical purpose for this organic material would be to support the furnace charge away from the base of the furnace during the initial phase of the smelt. This would not require a specific material, if

smelting was carried out in the winter as suggested then straw would have to be reserved for this process rather than using what was available easily.

The site of All Canning's Cross is considered to be one of the key sites of Iron Age Britain. The evidence from the samples available to analyse here indicates that several smelting events took place at this site. Considering the chemical differences between the samples it would appear that different methods or ores were employed over the occupation of the site. However, the recording of the site and deposition (and subsequent loss and rediscovery) of a limited and mixed sample of slag with no contextual information mean that it is very difficult to draw any conclusions more detailed than this about this site. This should not draw away from the importance of this site as a whole but it illustrates the issues that are present with basing theories on sites excavated and recorded without modern rigour.

Most of the sites sampled here utilised bog ore to produce phosphoric iron. As it is able to regenerate over time as new accumulations of iron rich material are formed in bogs it can be directly linked to the cosmology which appears to be universal across Iron Age Britain. It can take at least 20-30 years for a deposit to regenerate to the extent where it can be harvested again, this in a period where life is assumed to be short and brutal, would mean that to revisit the same deposit would require some extent of folk or oral history to transmit this information between generations. The recovery of bog ore could have been carried out at the same time as other activities in wetland areas, it may even have been more possible after other activities such as reed gathering had been carried out. The importance of phosphoric iron has been discussed elsewhere (Godfrey 2007) but as well as its mechanical properties (increased hardness, 'hot shortness') it also has resistance to corrosion. Being more resistant to corrosion, if placed in an open deposit it would remain metallic for longer, a factor that may have been important for objects intended for structured deposits.

Finally, while the production of iron on specialised smelting sites indicates a specialist skilled workforce. This craft specialisation has been seen as crucial to the understanding of middle to late Iron Age social organisation (Giles 2007b, 398). The scale of production observed at these sites indicates the production of iron with the intention of trade and exchange rather than simply for local consumption. The production of a consistent type of iron from the Berkshire cluster which matches the composition of the Datchet type of currency bar would suggest this area was producing iron for trade rather than local consumption. The foundation theories of iron production in Britain were laid down while there were still few confirmed smelting sites discovered. Those that had been identified were small scale and on settlement or defended sites. The discovery of more isolated sites and their dating to the Iron Age began a slow change in the theories of how iron was being produced but all too often these sites were dismissed as exceptional. Currency bars as a form of trade iron with morphological variation linked to geographical distribution indicate that there must have been specialised iron production centres such as the Berkshire and Foulness clusters across Britain. The skill of the Iron Age smith has not been underestimated to same extent as the individuals and groups who produced the raw material.

5.2 ROMAN

The Roman production of iron was dominated by concentrated production centres, The Weald, Forest of Dean and Northamptonshire Jurassic Ridge in Britain (Cleere 1981, 62) and Noricum and Spain in continental Europe (Pleiner 2000, 41). The Roman economy needed vast quantities of iron and steel, of an order of magnitude not previously seen in Britain. This scale of production would not have been possible using non-slag tapping technologies, the time and workforce would be impractical. Almost all of the samples analysed here from Roman contexts are consistent with slag tapping technologies, only the

samples from CQS represent a technology which is only partially consistent. To achieve a free running slag, essential for slag tapping, these sites have (generally) forfeited a substantial portion of the available iron from the ore into the slag. This loss of iron into the slag would have been more than made up for by the advantage of being able to extend a smelt to create a larger, more consolidated bloom. This equals more iron per smelt, skilled workers would be able to produce a greater volume of metal, they would consume greater volumes of raw materials but these could be sourced using unskilled labour. It has been estimated that of a population of 1.5 million then 4% of the total population would have been involved to some extent in the production of iron (Sim and Ridge 2002). Slag tapping techniques were brought to Britain prior to the arrival of the Romans, but their application was limited to the south eastern area of the country, which was in closest communication with the continent.

As well as a change in the scale of production and an almost universal use of slag tapping furnaces there was a shift in the type of ores being exploited in the Roman period. Geological sources rather than 'surface' sources such as bog ore were exploited. These would require a larger workforce to excavate the ores but would give concentrated clusters of raw material, this workforce could be less skilled but would also be specialised, focussed purely on the excavation of ore rather than in conjunction with another task. There are negative aspects to the use of these types of ore rather than the ores used in the Iron Age. As bog ore regenerated in the correct conditions then the same deposit could have been reused after a period of time, once geological ores have been depleted they do not regenerate. The larger deposits of geological ores would allow a site to continue operating until the locally available fuel was depleted. Unlike bog ore much (but not all) of the geological ores are phosphorus poor, this means that they are suitable for the production of low carbon steels.

Culturally the production of iron was taken from being a seasonal event embedded within an agricultural calendar to being an 'aseasonal' activity carried out on an industrial scale. The change in primary ore sources, from tertiary ores easily recovered from the surface or the immediate subsurface to geological ores, may be the result of imposing new external methods but it has greater impact. By specifically targeting ores which have to be excavated as a specialised task it isolates the process of ore collection severing connections with agriculture or other resource exploitation. This indicates a true level of specialisation being adopted in the Roman period, rather than a 'seasonal specialisation' apparent in the Iron Age.

While there would have also been ritual activity involved with smelting during the Roman period, there is no evidence from the sites or samples analysed here which would indicate religious or ritual activity. The ritual activity may have been carried out at a specific shrine location on a smelting site or away from the smelting site itself. The success of the smelt was left in the hands of the gods rather than a symbolic connection between the result of a previous success and the next.

5.3 TECHNICAL

The samples analysed here show that it is not possible to make sweeping statements regarding the efficiency of smelting technology in terms of the reduction level of furnaces from a whole period. The modern idea of efficiency, the percentage of iron reduced from the ore, is not a suitable measure for the bloomery process. The bloomery process has to be inefficient in this regard to successfully produce metallic iron, requiring iron oxide to flux the silica of the ore.

The widespread use of slag tapping furnaces would have resulted in larger and cleaner blooms being produced from each furnace. This can be seen as a more efficient use of

labour, the employment of the same number of people for an extended period, rather than doubling the labour to operate another furnace. Slag tapping relies on a free flowing slag; a result of the viscosity and liquidus temperature of the slag, both the result of the composition of the slag. The use of this method is a marked difference between most of the Iron Age and the Roman period, from the sites studied here, it is only the transitional site of Stockbury and the mid Roman site of Clearwell Quarry extension which have evidence for both technologies. The size of the larger furnaces excavated at Sindlesham could be seen as an attempt to increase the volume of metal produced from a single smelt without the knowledge of slag tapping or a true slag pit furnace of the type used by the 'Eastern Celts' from a similar period (Pleiner 2000, 60). Although this increase cannot compete with the increase possible from a slag tapping furnace.

An evolution of slag tapping was the opening of a small hole to tap slag from the furnace rather than opening the whole arch. This results in the formation of slag tubes, from the sites analysed as part of this thesis they are only present in Roman assemblages. They have also been identified in other Roman assemblages in Britain (Schrufer-Kolb 2004; Swiss and McDonnell 2004; Juleff *pers comm*) and also in Italy (Tizzoni and Tizzoni 2003). They offer a benefit to a tapping furnace as slag could be removed by the puncturing of a small hole in the front of the furnace, this would have been below the level of the slag bath and slag would have drained until it solidified within the furnace walls forming the slag tube. This would have kept the base of the furnace as a sealed unit, keeping the furnace closed would have kept the temperature and reduction conditions consistent within the furnace. Not having to reheat the furnace after each tapping episode would mean that less fuel and effort would be required. As it has been established that sites were located for fuel rather than ore this method of making the process more fuel efficient would have been beneficial. The presence of these tubes on most of the Roman sites analysed here and not the

transitional site of Stockbury shows that this may have been a particularly Roman method. To clarify this conclusion would require examination of further sites from the transition and early Roman period in Britain and a comparison to reports and sites in continental Europe.

Slag tapping requires a free flowing slag, a result of the liquidus temperature and the viscosity of the slag. All of the slag samples analysed have a melting temperature between 1150°C and 1250°C, however the viscosity of the samples shows a greater variation with the free flowing temperatures being between 1150°C and over 1350°C. While it is possible to increase the fluidity of the slag by increasing the temperature this also would increase the amount of furnace lining which would be melted into the slag. This would introduce alumina, lime and silica which would further increase the viscosity and increase the melting temperature. Interestingly the highest viscosity is from sites where slag tapping was being used (BP and SHF).

There appears to have been a change in the preferred types of ore exploited over the time period covered by this study. Tertiary ores dominate the Iron Age sites here, this is distorted by the Berkshire-Hampshire-Surrey cluster of sites, but sites outside this cluster also exploited tertiary ores (Paynter 2006; 2007). The Roman sites studied here exclusively exploited geological deposits which would have required prospecting and then excavation. Ore was excavated from pockets within the clay of the Weald (Cleere 1981, 132) and from open workings or Scowles in the Forest of Dean (Hoyle *et al.* 2007, 32). The exploitation of these different ores requires slightly different technologies, rather than the surface or immediate subsurface collection of ore from tertiary deposits the deeper geological deposits required excavation. Cleere and Crossley (1985, 53) observed a shift in the location of sites in the Sussex/Kent region during the 1st century BC from the chalk and greensands of Kent to the Wealden Beds. This also corresponds to a change in the furnace

technology and ore being exploited from the tertiary deposits to the siderite of the Wealden Beds (Paynter 2006, 287). This observed shift in this region seems to have been a conscious choice in conjunction with the adoption of slag tapping furnaces.

Iron smelting sites are known to have been located for fuel rather than other raw materials (McDonnell 1986, 20). But the use of fuel during a smelting event has not been considered in the same way. It appears from the samples analysed here, from both periods, that the amount of fuel used during a smelt was also an important factor. This is particularly clear with the development of the slag tube method of slag tapping, as discussed above. The lower reducing conditions at many of the furnaces would have required less fuel to achieve than more reducing conditions but at the sacrifice of volume of iron extracted from the ore or elevated carbon content. The higher levels of iron oxide present in the slag would also give a more liquid slag which would not need heating as far above its liquidus temperature. Increasing the temperature to make the slag more fluid would require increased airflow and fuel, having a more fluid slag makes the smelt more fuel efficient. There are samples from most sites which have higher reducing conditions but as shown by the analysis of the samples from Hartshill Copse there is possibility of variation in the reduction conditions within a single smelt.

5.4 Further Work

Many of the sites studied here were only accessible through museum collections or through pre-sampled assemblages, which imbues the material with inherent biases that cannot always be rectified. The lack of detailed excavation of iron smelting sites from both of these periods has limited the biases of some of this material; going forward I would echo the recommendations of Historic England (Dungworth *et al* 2015) and the Historical Metallurgical Society (Bayley *et al* 2008) and recommend the inclusion of

archaeometallurgical expertise earlier in the archaeological process than post excavation in order to maximise the potential of the data. If more sites were treated to the level of study that Peter and Susan Crew have brought to bear at Crawcwellt and Bryn Y Castell then we would be able to interrogate the evidence from sites more rigorously and be able to draw firmer conclusions than we can at present.

The dating of smelting sites from these sites can be difficult. Specialist smelting sites rarely have diagnostic artefactual assemblages that can accurately date the site typologically. Where sites are multi phased it can be difficult to determine the stratigraphic relationship between the smelts as furnaces can be isolated or simply capped by uniform secondary or tertiary deposits of slag. Scientific dating methods used correctly would help to resolve this but there are problems with calibration and a lack of desire to invest the resources into a series of dates. Radiocarbon dating in this period is hampered by the presence of a plateau on the calibration curve which leads to large error margins on the dates (Garrow *et al.* 2009). Dating fragments of charcoal trapped with the slag could help as it is guaranteed to be derived from the smelting process and it directly dates an individual smelt (Hendrickson *et al.* 2013). Dating in-slag charcoal from a number of furnaces may help to resolve the phasing of larger multi furnace sites. Archaeomagnetic dating can be used where furnace remains are present, however it requires regional calibration curves which are built from measurements taken from contemporary material. The curve is improving with ongoing work but currently the error range can limit the effectiveness of this method. It also requires in-situ furnace remains substantial enough for a series of samples to be taken.

5.5 SUMMARY

The conclusions drawn here are the result of these particular samples, a different set of samples could possibly produce different results. General trends such as the use of

phosphoric iron in the Iron Age and slag tapping technology during the Roman period are established in the orthodoxy and reinforced by this work. It has been possible to add detail to these with the cosmological connection to regenerative bog ore and the technical choice of tapping via a probed hole rather than an open arch. There are a number of differences in iron production between these two periods. Technically and economically there are clear differences in scale, the production sites of the Roman period are enormous, thousands of tonnes of waste products are estimated to remain on some sites. A significant increase from the largest Iron Age sites where tens of tonnes would be considered remarkable. While the samples here show that there was a change in the principle alloy of iron being produced, from phosphoric to carbon, it is not possible to make a broad statement over the quality of the iron. The quality of the iron produced is relative to what was desired rather than modern metallurgical desires. However it is possible to suggest that the trend from sites studied here that an efficiency of labour and fuel can be seen as having been important.

It can be said that while the differences in technical and economic parameters are the more easily defined the cultural differences are more important. Iron Age smelting can be interpreted as part of either a hierarchical or heterachical society, but it was a specialist activity that required planning over at least a whole agricultural cycle, for the gathering of raw materials and up to a generational scale, for the regeneration of raw materials. Those people carrying it out would have been supported by a wider community, but only for the period of the smelting campaign. It appears that smelting during the Roman period was a full time occupation, carried out throughout the year. The production of iron in the Iron Age appears to have been intrinsically linked to cosmological beliefs, the concept of regeneration can be identified in the use of bog ore and the use of different organic materials in the base of the furnace as a preparatory deposit to connect the smelt with previous successful applications of the iron. These aspects are not visible in the Roman

period, it is possible that the rituals associated with the successful production of iron were carried out away from the smelting location or in a form which does not leave a trace on site or in the slag.

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APPENDICES

APPENDIX A: IRON AGE SITES FULL CHEMICAL DATA

SADLER'S END SINDLESHAM (SES)

sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
SES 32 95 2015	1	b.d	0.6	3.4	24.1	4.0	1.3	2.7	b.d	0.4	63.7	100.0
	2	b.d	b.d	3.3	22.6	3.5	0.8	2.4	b.d	b,d	67.5	100.0
	3	b.d	b.d	2.5	23.4	3.5	0.8	2.4	b.d	b.d	67.4	100.0
	4	b.d	0.6	2.4	21.2	3.4	0.5	2.1	b.d	b.d	69.7	100.0
	5	b.d	b.d	3.1	23.1	4.0	1.5	2.7	b.d	b.d	65.7	100.0
	mean	b.d	0.6	3.0	22.9	3.7	0.9	2.4	b.d	0.4	66.8	100.7
SES U/S Section	1	b.d	b.d	3.5	31.2	2.8	1.7	1.5	b.d	0.4	58.4	100.0
	2	b.d	b.d	3.9	30.6	4.8	1.8	2.4	b.d	b.d	56.6	100.0
	3	b.d	b.d	3.1	34.5	4.5	1.4	1.7	b.d	b.d	54.9	100.0
	4	b.d	b.d	4.2	36.9	4.2	2.4	1.9	b.d	b.d	49.8	100.0
	5	b.d	b.d	4.6	32.4	4.8	2.6	2.7	b.d	b.d	52.9	100.0
	mean	b.d	b.d	3.8	33.1	4.2	2.0	2.1	b.d	0.4	54.5	100.1
SES no #	1	b.d	b.d	4.0	23.4	2.9	1.8	2.1	b.d	0.4	65.6	100.0
	2	b.d	0.4	2.5	24.1	1.9	0.8	1.5	b.d	0.4	68.2	100.0
	3	b.d	0.4	2.8	25.7	2.6	1.2	1.6	b.d	b.d	65.8	100.0
	4	b.d	0.5	2.6	24.0	2.6	1.1	1.8	b.d	b.d	67.4	100.0
	5	b.d	0.5	2.5	23.9	2.4	1.2	1.6	b.d	b.d	68.0	100.0
	mean	b.d	0.4	2.9	24.2	2.5	1.2	1.7	b.d	0.4	67.0	100.3
SES 263 375 3	1	b.d	b.d	5.0	26.6	3.8	2.0	2.6	b.d	b.d	60.0	100.0
	2	b.d	0.5	4.3	27.1	3.7	2.1	2.4	b.d	b.d	60.0	100.0
	3	b.d	0.6	1.8	25.8	1.3	0.7	1.0	b.d	0.4	68.5	100.0
	4	b.d	b.d	4.5	23.6	3.9	2.1	2.4	b.d	b.d	63.5	100.0
	5	b.d	0.4	2.7	24.6	2.9	1.3	1.9	b.d	b.d	66.2	100.0
	6	b.d	0.5	2.4	24.7	2.6	0.9	1.7	b.d	0.3	66.9	100.0
	7	b.d	b.d	4.9	29.4	3.4	1.6	1.9	b.d	0.4	58.0	100.0
	mean	b.d	0.5	3.7	26.0	3.1	1.5	2.0	b.d	0.4	63.3	100.4

sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
SES 263 375 base	1	b.d	0.4	2.6	23.6	2.3	1.2	1.6	b.d	b.d	68.3	100.0
	2	b.d	0.4	2.7	23.9	2.4	1.1	1.5	b.d	0.3	67.7	100.0
	3	b.d	0.4	3.3	25.7	2.7	1.6	1.8	b.d	0.3	64.2	100.0
	4	b.d	0.5	2.4	24.0	2.0	0.9	1.5	b.d	0.4	68.4	100.0
	5	b.d	0.4	2.4	25.3	2.1	1.0	1.3	b.d		67.6	100.0
	6	b.d	b.d	3.2	25.2	2.7	1.5	2.1	b.d	0.4	65.1	100.0
	7	b.d	0.4	3.6	25.7	2.8	1.6	2.0	b.d	0.4	63.6	100.0
	8	b.d	0.4	3.4	25.7	2.7	1.8	2.1	b.d	0.4	63.5	100.0
	mean	b.d	0.4	3.0	24.9	2.5	1.3	1.7	b.d	0.3	66.1	100.1
SES LM 2	1	b.d	0.4	3.4	20.0	3.1	0.4	0.6	b.d	b.d	72.1	100.0
	2	b.d	0.4	4.4	21.9	5.0	0.7	1.3	b.d	b.d	66.3	100.0
	3	b.d	b.d	3.2	25.9	3.3	0.6	0.9	b.d	b.d	66.1	100.0
	4	b.d	b.d	2.9	19.4	4.3	0.7	1.1	b.d	0.4	71.3	100.0
	5	b.d	b.d	4.4	17.1	6.7		1.5	b.d	b.d	70.3	100.0
	mean	b.d	0.4	3.6	20.9	4.5	0.6	1.1	b.d	0.4	69.2	100.7
SES 263 375 top	1	b.d	b.d	0.5	1.4	26.4	1.5	0.5	0.8	0.4	68.6	100.0
	2	b.d	b.d	0.4	3.2	27.5	1.6	1.5	1.0	0.3	64.6	100.0
	3	b.d	b.d	b.d	2.3	24.4	2.2	0.5	1.3	0.3	69.1	100.0
	4	b.d	b.d	b.d	1.3	20.6	2.1	0.2	0.6	b.d	75.1	100.0
	5	b.d	b.d	0.4	3.7	27.7	2.0	1.8	1.1	0.4	63.0	100.0
	mean	b.d	b.d	0.4	2.4	25.3	1.9	0.9	1.0	0.3	68.1	100.2
SES LM Top	1	b.d	0.4	2.1	23.4	2.1	0.4	0.7	b.d	b.d	71.0	100.0
	2	b.d	b.d	3.7	22.9	4.1	1.4	1.7	b.d	b.d	66.2	100.0
	3	b.d	b.d	2.9	23.3	5.3	1.3	2.3	b.d	b.d	64.9	100.0
	4	b.d	b.d	5.0	21.1	4.3	1.0	1.5	b.d	b.d	67.1	100.0
	5	b.d	b.d	4.6	23.2	4.4	1.7	1.6	b.d	b.d	64.6	100.0
	6	b.d	b.d	3.6	19.8	5.4	1.3	2.3	b.d	b.d	67.6	100.0
	mean	b.d	0.4	3.6	22.3	4.3	1.2	1.7	b.d	b.d	66.9	100.3

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
SES 221 286 2015 1	1	1.1	b.d	5.9	24.8	4.8	1.3	3.0	b.d	b.d	59.1	100.0
	2	b.d	0.6	1.9	25.1	3.0		1.9	b.d	b.d	67.6	100.0
	3	0.7	0.3	5.1	24.9	4.2	1.3	2.8	b.d	b.d	60.7	100.0
	4	0.7	0.6	3.6	22.9	3.1		2.0	b.d	b.d	67.0	100.0
	5	0.7	0.5	3.4	25.4	3.2	0.3	2.1	b.d	b.d	64.4	100.0
	6	1.3	0.4	5.4	23.5	4.3	0.4	2.7	b.d	b.d	62.0	100.0
	mean	0.9	0.5	4.2	24.4	3.8	0.8	2.4	b.d	b.d	63.5	100.5
SES LM B	1	b.d	0.4	3.4	24.3	2.0	b.d	0.4	b.d	b.d	69.4	100.0
	2	b.d	b.d	3.7	15.5	2.1	1.4	b.d	b.d	b.d	77.3	100.0
	3	b.d	0.5	2.1	23.5	3.3	b.d	0.4	b.d	b.d	70.2	100.0
	4	b.d	0.6	4.3	25.4	2.7	b.d	0.6	b.d	0.2	66.4	100.0
	5	b.d	0.5	5.7	20.3	2.6	0.3	0.6	b.d	b.d	70.0	100.0
	6	b.d	0.4	4.8	23.6	2.2	b.d	0.4	b.d	b.d	68.6	100.0
	mean	b.d	0.5	4.0	22.1	2.5	0.8	0.5	b.d	0.2	70.3	100.9
SES U/S B	1	b.d	0.4	3.6	27.5	4.2	2.0	2.5	b.d	0.3	59.6	100.0
	2	0.6	0.3	3.9	26.3	4.5	1.4	2.9	b.d	b.d	60.1	100.0
	3	b.d	0.5	2.5	28.6	2.2	1.3	1.5	b.d	0.2	63.2	100.0
	4	b.d	0.3	3.5	30.1	3.5	2.3	2.2	b.d	b.d	58.2	100.0
	5	b.d	3.4	b.d	28.0	5.1	2.0	2.9	b.d	b.d	58.6	100.0
	6	b.d	2.8	b.d	31.4	3.6	1.5	1.9	b.d	0.3	58.6	100.0
	mean	0.6	1.3	3.4	28.6	3.8	1.7	2.3	b.d	0.2	59.7	101.7
SES 32 95	1	b.d	0.4	3.0	20.4	3.6	0.6	2.4	b.d	0.6	69.1	100.0
	2	0.5	b.d	2.4	20.7	3.4	0.7	2.4	b.d	0.4	69.4	100.0
	3	b.d	0.4	2.9	21.8	3.9	1.4	2.6	b.d	0.3	66.6	100.0
	4	b.d	0.5	2.6	20.6	3.9	0.4	2.7	b.d	0.4	69.0	100.0
	5	b.d	b.d	2.8	22.2	3.8	1.1	2.5	b.d	0.4	67.1	100.0
	6	b.d	0.5	2.7	21.8	3.4	1.2	2.5	b.d	0.3	67.6	100.0
	mean	0.5	0.4	2.7	21.2	3.7	0.9	2.5	0.0	0.4	68.1	100.6

GRAZELEY ROAD READING (GRR)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
GRR 3063	1	b.d	0.4	1.4	25.3	2.4	b.d	0.7	b.d	0.5	69.4	100.0
	2	0.9	b.d	3.1	23.9	4.0	0.5	1.2	b.d	0.6	65.9	100.0
	3	0.8	b.d	3.3	23.0	4.2	0.8	1.3	b.d	0.4	66.4	100.0
	4	0.4	0.3	2.4	23.7	3.3	0.2	1.2	b.d	0.6	67.9	100.0
	5	0.7	b.d	3.7	19.8	5.3	0.5	1.5	b.d	0.4	68.1	100.0
	mean	0.7	0.4	2.8	23.1	3.8	0.5	1.2	b.d	0.5	67.6	100.4
GRR 3062	1	b.d	b.d	3.3	23.8	2.7	b.d	0.7	b.d	0.4	69.3	100.0
	2	b.d	b.d	2.4	23.4	3.1	b.d	0.6	b.d	0.6	69.5	100.0
	3	b.d	b.d	2.8	23.6	2.5	b.d	0.5	b.d	0.4	70.2	100.0
	4	b.d	b.d	2.4	23.7	2.7	b.d	0.5	b.d	0.5	70.3	100.0
	5	b.d	b.d	2.0	24.7	2.1	b.d	0.4	b.d	0.6	70.2	100.0
	mean	b.d	b.d	2.6	23.8	2.6	b.d	0.5	b.d	0.5	69.9	99.9
GRR 3064	1	b.d	b.d	1.5	17.1	2.5	b.d	0.9	b.d	0.4	77.5	100.0
	2	b.d	b.d	1.5	16.1	2.0	b.d	0.7	b.d	b.d	79.7	100.0
	3	b.d	b.d	1.9	18.7	2.3	b.d	1.0	b.d	b.d	76.1	100.0
	4	b.d	b.d	1.8	14.8	2.9	b.d	1.1	b.d	0.6	78.9	100.0
	5	0.6	b.d	3.4	22.5	3.5	b.d	0.4	b.d	1.1	68.4	100.0
	6	b.d	b.d	2.2	19.9	3.2	b.d	0.9	b.d	0.5	73.3	100.0
	7	b.d	b.d	1.4	13.7	2.5	b.d	0.7	b.d	b.d	81.7	100.0
	mean	0.6	b.d	1.9	17.5	2.7	b.d	0.8	b.d	0.7	76.5	100.8
GRR 3062.2	1	b.d	b.d	3.2	24.3	2.4	0.3	0.6	b.d	0.5	68.7	100.0
	2	b.d	b.d	2.4	24.6	1.9	0.2	0.5	b.d	0.5	69.9	100.0
	3	b.d	b.d	2.5	24.4	2.2	b.d	0.5	b.d	0.6	69.8	100.0
	4	b.d	b.d	3.4	23.7	3.3	b.d	0.8	b.d	0.5	68.5	100.0
	5	0.8	b.d	4.5	23.3	3.1	b.d	0.6	b.d	0.4	67.4	100.0
	6	b.d	b.d	3.0	24.7	2.5	0.3	0.5	b.d	0.6	68.5	100.0
	7	b.d	0.4	0.7	25.9	0.6	b.d	b.d	b.d	0.6	71.8	100.0
	mean	0.8	0.4	2.8	24.4	2.3	0.3	0.6	b.d	0.5	69.2	101.3

MANOR FARM FINCHAMPSTEAD (MFF)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
MFF 15 2015	1	b.d	b.d	2.2	25.7	3.2	b.d	0.6	b.d	b.d	68.3	100.0
	2	b.d	b.d	2.0	26.8	3.6	0.7	0.8	b.d	b.d	66.1	100.0
	3	b.d	b.d	1.7	25.4	3.6	b.d	0.9	b.d	b.d	68.4	100.0
	4	b.d	b.d	2.7	24.5	4.3	0.5	1.2	b.d	b.d	66.7	100.0
	5	b.d	b.d	1.3	25.1	4.8	0.4	1.0	b.d	0.3	67.1	100.0
	mean	b.d	b.d	2.0	25.5	3.9	0.5	0.9	b.d	0.3	67.3	100.5
MFF 9 2015 1	1	b.d	b.d	1.6	23.8	2.8	b.d	1.0	b.d	b.d	70.8	100.0
	2	b.d	b.d	1.6	23.7	3.7	0.3	1.3	b.d	b.d	69.5	100.0
	3	b.d	b.d	1.6	23.3	3.3	0.3	1.0	b.d	0.4	70.2	100.0
	4	b.d	b.d	1.7	23.2	3.8	0.3	1.0	b.d	b.d	69.9	100.0
	5	b.d	b.d	1.9	23.6	3.8	0.3	1.2	b.d	b.d	69.2	100.0
	mean	b.d	b.d	1.7	23.5	3.5	0.3	1.1	b.d	0.4	69.9	100.4
MFF 9.1	1	b.d	b.d	2.0	22.6	4.4	0.3	1.6	b.d	b.d	69.2	100.0
	2	b.d	b.d	1.6	24.3	3.3	0.3	1.1	b.d	b.d	69.4	100.0
	3	b.d	b.d	1.9	22.9	3.8	0.4	1.1	b.d	b.d	69.9	100.0
	4	b.d	b.d	2.2	22.2	4.8	0.5	1.6	b.d	b.d	68.9	100.0
	5	b.d	b.d	1.6	22.7	3.8	0.4	1.3	b.d	b.d	70.4	100.0
	6	b.d	b.d	1.9	22.4	4.4	0.4	1.3	b.d	b.d	69.7	100.0
	7	b.d	b.d	2.0	22.5	3.6	0.4	1.0	b.d	b.d	70.5	100.0
	mean	b.d	b.d	1.9	22.8	4.0	0.4	1.3	b.d	b.d	69.7	100.0
MFF 15 2015 1	1	b.d	0.4	1.0	23.0	4.7	0.3	2.1	b.d	b.d	68.7	100.0
	2	b.d	b.d	0.8	20.6	4.8	b.d	1.9	b.d	b.d	72.0	100.0
	3	b.d	0.4	1.6	22.1	5.8	0.4	2.4	b.d	b.d	67.4	100.0
	4	b.d	0.4	0.8	18.5	3.8	0.2	1.7	b.d	0.3	74.3	100.0
	5	b.d	0.6	1.2	23.1	3.4	b.d	1.5	b.d	b.d	70.3	100.0
	6	b.d	0.5	0.6	24.9	3.4	0.2	1.5	b.d	0.4	68.5	100.0
	mean	b.d	0.4	1.0	22.0	4.3	0.2	1.8	b.d	0.3	70.2	100.4
MFF 15 2015 2	1	b.d	b.d	2.3	25.7	4.0	b.d	0.7	b.d	b.d	67.5	100.0

	2	b.d	b.d	1.7	24.8	5.2	0.5	1.5	b.d	b.d	66.4	100.0
	3	b.d	b.d	2.2	24.4	5.4	0.5	1.5	b.d	b.d	66.0	100.0
	4	b.d	b.d	2.4	24.6	5.2	0.6	1.7	b.d	b.d	65.6	100.0
	mean	b.d	b.d	2.2	24.8	4.9	0.5	1.3	b.d	b.d	66.4	100.1

HARTSHILL COPSE, UPPER BUCKLEBURY (HCB)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
HCB 36342	1	b.d	0.4	4.7	25.2	1.2	0.6	1.3	0.3	1.2	65.2	100.0
	2	b.d	0.5	5.4	27.2	1.3	1.0	1.1	b.d	1.0	62.5	100.0
	3	b.d	b.d	5.7	26.9	1.2	0.2	1.1	b.d	1.0	63.8	99.8
	4	b.d	b.d	4.5	22.0	1.0	0.7	0.9	b.d	1.0	69.8	100.0
	5	b.d	b.d	5.5	24.2	1.4	0.6	1.6	b.d	1.0	65.8	100.0
	mean	b.d	0.5	5.1	25.1	1.2	0.6	1.2	0.3	1.0	65.4	100.5
HCB 36343	1	0.5	b.d	5.9	25.9	1.2	0.9	1.3	b.d	1.1	63.2	100.0
	2	0.7	b.d	6.1	27.9	1.4	0.9	1.1	b.d	1.1	60.8	100.0
	3	b.d	0.4	5.5	29.1	1.2	1.2	0.9	b.d	1.2	60.4	100.0
	4	b.d	0.5	4.9	28.5	1.1	0.8	0.8	b.d	1.3	62.0	100.0
	5	b.d	b.d	4.6	27.8	0.9	0.3	0.8	b.d	1.2	64.4	100.0
	6	b.d	0.5	5.3	28.9	1.2	0.9	1.0	b.d	1.4	60.9	100.0
	mean	0.6	0.5	5.4	28.0	1.2	0.8	1.0	b.d	1.2	61.9	100.6
HCB 36342	1	b.d	b.d	6.3	28.1	1.1	1.1	0.8	b.d	1.1	61.5	100.0
	2	b.d	0.6	3.1	27.1	0.9	0.3	0.8	b.d	1.4	65.9	100.0
	3	b.d	0.7	4.0	27.4	0.8	0.9	0.6	b.d	1.3	64.1	100.0
	4	b.d	b.d	4.5	45.9	1.2	1.0	1.2	b.d	b.d	46.2	100.0
	5	b.d	b.d	8.6	31.7	1.3	3.3	0.9	b.d	0.9	53.3	100.0
	mean	b.d	0.6	5.3	32.0	1.0	1.4	0.9	b.d	1.2	58.2	100.6
HCB 36345	1	0.5	b.d	6.0	29.6	1.5	0.7	1.2	0.4	1.0	59.1	100.0
	2	b.d	b.d	7.6	28.4	1.7	0.5	1.5	0.4	1.0	59.0	100.0
	3	0.7	b.d	9.0	28.1	2.9	0.9	3.1	0.8	0.7	53.7	100.0
	4	b.d	0.4	7.6	30.3	1.6	1.5	1.2	0.3	1.1	56.0	100.0

	5	0.5	b.d	6.4	29.8	1.6	0.8	1.3	0.3	1.1	58.3	100.0
	mean	0.6	0.4	7.3	29.2	1.8	0.9	1.7	0.4	1.0	57.2	100.6
HCB 36341	1	b.d	b.d	5.8	27.3	0.9	1.5	0.9	b.d	1.3	62.3	100.0
	2	b.d	b.d	4.1	26.8	1.1	1.0	0.9	b.d	1.1	65.0	100.0
	3	b.d	b.d	5.1	26.6	0.9	0.9	0.9	b.d	1.2	64.4	100.0
	4	b.d	b.d	5.9	26.9	1.4	1.2	1.1	b.d	1.0	62.6	100.0
	5	b.d	b.d	5.7	27.0	1.0	1.5	0.9	b.d	1.1	62.8	100.0
	6	b.d	b.d	5.0	27.3	0.9	1.5	1.0	b.d	1.2	63.2	100.0
	mean	b.d	b.d	5.3	27.0	1.0	1.3	0.9	b.d	1.2	63.4	100.0

MATTHEW'S GREEN, WOKINGHAM (MGE)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
MGE 5734	1	0.5	b.d	4.3	25.1	2.1	1.3	1.1	b.d	0.5	65.3	100.0
	2	b.d	b.d	5.2	28.8	2.1	0.9	1.1	b.d	0.5	61.5	100.0
	3	b.d	b.d	4.0	26.3	1.9	0.4	0.7	b.d	0.6	66.3	100.0
	4	b.d	b.d	2.6	25.8	1.3	0.3	0.5	b.d	0.5	69.1	100.0
	5	0.4	0.3	3.9	26.5	1.8	1.2	1.1	b.d	0.4	64.5	100.0
	6	0.3	0.4	3.3	24.1	1.6	0.8	0.8	b.d	0.5	68.2	100.0
	7	0.4	0.4	4.8	28.5	1.5	1.1	0.8	b.d	0.4	62.1	100.0
	mean	0.4	0.4	4.0	26.4	1.7	0.8	0.9	b.d	0.5	65.3	100.4
MGE 2671	1	b.d	0.4	4.6	29.6	2.3	1.6	1.3	b.d	0.8	59.6	100.0
	2	b.d	0.4	4.4	30.2	2.4	1.5	1.3	b.d	0.9	59.1	100.0
	3	0.5	0.3	4.5	30.5	2.3	1.6	1.5	0.3	0.8	57.7	100.0
	4	0.7	0.3	4.6	29.8	2.1	1.7	1.6	b.d	0.8	58.4	100.0
	5	0.3	0.3	4.8	30.0	2.2	1.6	1.3	b.d	0.9	58.6	100.0
	6	0.7	0.5	4.3	30.7	2.2	1.6	1.5	b.d	0.9	57.6	100.0
	7	b.d	0.4	4.4	30.7	2.4	1.6	1.4	b.d	0.8	58.3	100.0
	mean	0.5	0.4	4.5	30.2	2.3	1.6	1.4	0.3	0.8	58.5	100.5
MGE 6511	1	0.7	b.d	4.9	22.8	6.3	0.6	2.3	b.d	0.5	61.9	100.0

	2	0.4	b.d	5.7	21.6	6.7	1.3	2.7	b.d	0.5	61.1	100.0
	3	0.5	b.d	5.0	21.4	6.0	0.7	2.4	b.d	0.4	63.6	100.0
	4	b.d	b.d	2.5	20.2	5.0	0.2	2.2	b.d	0.5	69.4	100.0
	5	b.d	b.d	4.2	21.9	5.0	0.3	2.0	b.d	0.6	65.9	99.7
	6	1.0	b.d	4.9	22.2	6.1	0.5	2.3	b.d	0.5	62.5	100.0
	mean	0.7	b.d	4.5	21.7	5.9	0.6	2.3	b.d	0.5	64.0	100.2
MGE 5731	1	b.d	b.d	3.0	19.9	3.6	0.2	1.7	b.d	0.4	71.2	100.0
	2	b.d	b.d	2.7	19.5	3.4	0.3	1.5	b.d	b.d	72.6	100.0
	3	b.d	b.d	2.9	19.2	2.8	0.2	1.2	b.d	b.d	73.8	100.0
	4	b.d	b.d	3.2	19.9	3.4	b.d	1.5	b.d	b.d	71.9	100.0
	5	b.d	b.d	1.8	19.5	1.9	b.d	0.8	b.d	b.d	76.0	100.0
	6	b.d	b.d	2.4	18.7	3.4	b.d	1.8	b.d	0.4	73.3	100.0
	7	b.d	b.d	5.1	15.3	6.6	0.3	3.2	b.d	0.4	69.2	100.0
	mean	b.d	b.d	3.0	18.9	3.6	0.2	1.7	b.d	0.4	72.6	100.3
MGE 5733	1	0.6	1.2	3.0	27.0	3.9	1.0	2.7	b.d	0.4	60.4	100.0
	2	b.d	1.1	3.1	24.2	3.2	1.9	3.0	b.d	b.d	63.6	100.0
	3	b.d	1.1	1.9	24.5	2.7	1.3	1.7	b.d	0.4	66.6	100.0
	4	0.4	0.6	2.0	23.2	4.0	1.3	2.5	b.d	b.d	66.2	100.0
	5	0.4	0.7	2.8	24.8	3.0	1.3	1.9	b.d	0.5	64.7	100.0
	6	0.6	1.4	2.9	27.7	3.6	1.4	2.8	b.d	0.4	59.3	100.0
	7	0.4	1.2	2.9	25.1	3.5	2.0	3.3	b.d	b.d	61.6	100.0
	mean	0.5	1.0	2.6	25.2	3.4	1.4	2.5	b.d	0.4	63.2	100.3

SHOOTER'S HILL, LONDON (SHH)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
IW - 040 SHH	1	b.d	0.6	4.3	23.8	0.8	0.7	5.1	b.d	0.3	64.5	100.0
	2	b.d	0.6	3.9	24.8	0.8	0.8	5.5	b.d	0.3	63.2	100.0
	3	b.d	0.7	4.1	24.4	0.8	0.8	5.5	b.d	0.3	63.5	100.0
	4	b.d	0.6	4.0	25.0	0.9	0.6	5.2	b.d	0.4	63.4	100.0
	5	b.d	0.7	4.0	23.9	0.9	0.7	5.4	b.d	0.4	64.1	100.0

	6	b.d	0.7	4.1	24.0	0.8	0.6	5.4	b.d	b.d	64.4	100.0
	mean	b.d	0.6	4.1	24.3	0.8	0.7	5.3	b.d	0.3	63.9	100.1
IW - 041 SHH	1	b.d	b.d	2.4	26.0	1.9	0.5	3.1	b.d	b.d	66.2	100.0
	2	b.d	0.5	2.2	25.9	1.5	0.4	2.6	b.d	b.d	66.9	100.0
	3	b.d	0.4	2.7	26.8	2.1	0.5	3.2	b.d	b.d	64.3	100.0
	4	b.d	b.d	3.5	25.4	2.3	0.7	4.2	b.d	b.d	63.9	100.0
	5	b.d	b.d	2.7	27.3	1.7	0.3	2.8	b.d	b.d	65.3	100.0
	mean	b.d	0.4	2.7	26.3	1.9	0.5	3.2	b.d	b.d	65.3	100.2
IW - 042 SHH	1	b.d	0.6	4.3	21.0	0.8	0.9	3.9	b.d	b.d	68.5	100.0
	2	b.d	0.4	3.8	20.9	0.7	0.8	3.7	b.d	0.3	69.5	100.0
	3	0.4	0.6	3.3	21.2	0.7	0.7	3.3	b.d	b.d	69.8	100.0
	4	b.d	1.1	2.6	24.3	0.6	0.6	2.6	b.d	0.3	67.9	100.0
	5	b.d	0.9	2.0	24.8	b.d	0.4	2.0	b.d	b.d	70.0	100.0
	mean	0.4	0.7	3.2	22.4	0.7	0.7	3.1	b.d	0.3	69.1	100.6

LIGHTWATER, SURREY (LW)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
IW 036 LW	1	0.9	0.4	6.6	18.0	b.d	0.9	0.8	b.d	14.3	58.1	100.0
	2	b.d	b.d	0.7	26.5	8.2	0.6	2.3	b.d	0.7	61.1	100.0
	3	b.d	b.d	0.8	27.8	6.5	0.6	2.1	b.d	0.6	61.6	100.0
	4	b.d	b.d	0.8	27.8	7.7	0.7	2.1	b.d	0.4	60.7	100.0
	5	b.d	b.d	0.4	26.1	6.3	0.6	2.0	b.d	0.6	64.0	100.0
	6	b.d	0.4	b.d	25.8	7.2	0.6	1.8	b.d	0.5	63.8	100.0
	mean	0.9	0.4	1.8	25.3	7.2	0.7	1.8	b.d	2.8	61.5	102.5
IW 038 LW	1	b.d	b.d	2.0	25.2	5.7	0.2	1.8	b.d	1.3	63.8	100.0
	2	b.d	b.d	1.9	27.1	5.6	0.2	1.9	b.d	1.4	62.0	100.0
	3	b.d	b.d	2.0	25.1	5.9	b.d	1.8	b.d	1.3	63.8	100.0
	4	b.d	0.5	1.5	25.3	4.9	b.d	1.5	b.d	1.5	64.8	100.0
	5	b.d	b.d	2.0	25.9	6.6	0.3	2.2	b.d	1.3	61.7	100.0
	6	b.d	0.4	2.1	28.2	6.4	0.3	2.1	b.d	1.4	59.2	100.0
	mean	b.d	0.5	1.9	26.2	5.8	0.2	1.9	b.d	1.4	62.6	100.4
IW 037 LW	1	b.d	b.d	3.2	27.9	5.9	1.4	1.8	b.d	1.0	58.8	100.0
	2	b.d	0.6	2.6	27.3	6.7	1.3	1.9	b.d	1.0	58.7	100.0
	3	b.d	b.d	2.9	28.4	5.3	1.2	1.8	b.d	1.0	59.3	100.0
	4	b.d	0.4	2.3	27.4	4.9	0.9	1.5	b.d	0.8	61.7	100.0
	5	b.d	0.5	1.5	28.0	4.3	0.5	1.1	b.d	0.9	63.2	100.0
	6	b.d	b.d	1.9	27.8	5.2	0.8	1.6	b.d	0.9	61.8	100.0
	7	b.d	b.d	2.6	27.0	6.3	1.2	1.8	b.d	1.0	60.1	100.0
	mean	b.d	0.5	2.4	27.7	5.5	1.1	1.6	b.d	1.0	60.5	100.3
IW 053 LW	1	b.d	b.d	0.8	24.9	5.6	0.4	1.6	b.d	0.7	66.1	100.0
	2	b.d	b.d	0.8	25.8	4.9	0.3	1.6	b.d	0.6	66.0	100.0
	3	b.d	b.d	0.8	26.3	4.7	b.d	1.2	b.d	b.d	67.1	100.0
	4	b.d	b.d	1.0	24.7	5.7	0.4	1.5	b.d	0.8	65.9	100.0
	5	b.d	b.d	0.8	24.5	6.7	0.7	2.1	b.d	0.7	64.6	100.0

	6	b.d	b.d	0.7	25.7	4.6	0.4	1.5	b.d	0.7	66.3	100.0
	mean	b.d	b.d	0.8	25.3	5.4	0.4	1.6	b.d	0.7	66.0	100.2
IW 055 LW	1	b.d	b.d	0.3	17.5	3.3	0.2	0.7	b.d	b.d	78.0	100.0
	2	b.d	0.3	b.d	20.0	3.4	0.2	0.8	b.d	0.4	74.9	100.0
	3	b.d	b.d	0.3	17.6	5.9	0.4	1.4	b.d	0.4	74.0	100.0
	4	b.d	b.d	0.4	22.7	5.2	0.3	1.3	b.d	0.4	69.7	100.0
	5	b.d	b.d	0.5	16.9	8.9	0.7	1.5	b.d	0.3	71.2	100.0
	6	b.d	b.d	b.d	20.7	2.6	0.2	0.5	b.d	0.4	75.7	100.0
	7	b.d	0.3	0.3	21.1	3.9	0.2	0.8	b.d	0.3	73.1	100.0
	mean	b.d	0.3	0.4	19.5	4.8	0.3	1.0	b.d	0.4	73.8	100.4
IW - 059 LW	1	b.d	1.3	7.9	28.1	0.8	2.2	4.4	b.d	0.5	54.9	100.0
	2	b.d	1.3	7.9	30.0	b.d	1.9	3.8	b.d	0.6	54.6	100.0
	3	b.d	1.3	8.2	29.2	0.9	2.1	4.2	b.d	0.7	53.4	100.0
	4	b.d	1.3	8.1	28.6	0.7	2.6	4.7	b.d	0.7	53.2	100.0
	5	b.d	1.5	7.1	28.9	b.d	2.3	4.2	b.d	0.6	55.3	100.0
	6	b.d	1.3	8.4	28.0	b.d	2.3	4.5	b.d	0.6	54.9	100.0
	7	b.d	1.5	8.0	28.1	0.9	2.2	4.5	b.d	0.6	54.2	100.0
	mean	b.d	1.3	7.9	28.7	0.9	2.2	4.3	b.d	0.6	54.4	100.4

ALL CANNING'S CROSS (ACC)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
ACC 10	1	b.d	b.d	3.0	25.2	b.d	0.7	1.0	b.d	b.d	70.2	100.0
	2	b.d	0.9	1.4	26.4	b.d	b.d	0.8	b.d	b.d	70.5	100.0
	3	b.d	b.d	2.8	28.1	b.d	b.d	1.0	b.d	b.d	68.1	100.0
	4	b.d	b.d	4.0	29.6	b.d	1.2	1.9	b.d	b.d	63.2	100.0
	5	b.d	b.d	4.0	29.6	b.d	1.2	1.9	b.d	b.d	63.2	100.0
	6	b.d	0.9	4.2	29.4	b.d	1.2	2.2	b.d	b.d	62.2	100.0
	7	b.d	0.7	4.0	28.0	b.d	2.2	2.2	b.d	b.d	62.9	100.0
	mean	b.d	0.8	3.3	28.0	b.d	1.3	1.6	b.d	b.d	65.8	100.8
ACC 1	1	1.0	0.9	12.7	33.1	b.d	2.0	1.7	b.d	0.9	47.9	100.0
	2	b.d	b.d	11.6	33.8	1.0	2.9	1.6	b.d	0.9	48.2	100.0
	3	b.d	0.8	11.4	33.2	1.1	2.4	1.6	b.d	1.1	48.4	100.0
	4	b.d	1.0	11.0	33.3	1.0	3.0	1.6	b.d	1.1	48.0	100.0
	5	b.d	b.d	11.8	33.2	b.d	2.1	1.8	b.d	1.2	49.9	100.0

	6	b.d	b.d	10.0	32.5	1.1	3.1	1.3	b.d	0.9	51.1	100.0
	7	b.d	b.d	9.4	32.7	b.d	3.6	0.9	b.d	1.2	52.2	100.0
	8	b.d	b.d	10.3	32.5	1.1	3.2	1.1	b.d	b.d	51.9	100.0
	9	b.d	0.7	10.0	32.2	b.d	3.0	1.1	b.d	0.7	52.3	100.0
	10	b.d	1.0	10.2	31.7	b.d	2.9	1.1	b.d	0.7	52.5	100.0
	11	b.d	1.0	10.2	31.7	b.d	2.9	1.1	b.d	0.7	52.5	100.0
	12	b.d	b.d	9.6	32.2	b.d	2.1	1.4	b.d	1.1	53.7	100.0
	mean	1.0	0.9	10.7	32.7	1.1	2.8	1.3	b.d	0.9	50.7	102.1
ACC 6	1	b.d	b.d	7.3	21.6	1.2	0.8	0.8	b.d	0.7	67.8	100.0
	2	b.d	b.d	6.8	21.3	1.2	1.0	0.7	0.7	0.6	67.7	100.0
	3	b.d	b.d	4.9	17.0	1.6	b.d	0.5	b.d	b.d	75.9	100.0
	4	b.d	b.d	4.9	17.0	1.6	b.d	0.5	b.d	b.d	75.9	100.0
	5	b.d	0.9	7.0	22.1	1.2	1.0	0.5	b.d	b.d	67.4	100.0
	6	b.d	b.d	7.2	22.2	1.5	0.7	b.d	b.d	b.d	68.4	100.0
	7	b.d	b.d	7.2	21.9	1.5	0.7	b.d	b.d	0.7	67.9	100.0
	mean	b.d	0.9	6.5	20.5	1.4	0.8	0.6	0.7	0.7	70.2	102.2

ACC 7	1	b.d	b.d	6.9	21.6	1.1	0.7	0.6	b.d	0.9	68.3	100.0
	2	b.d	0.7	6.6	22.1	1.1	0.7	0.5	b.d	b.d	68.3	100.0
	3	b.d	0.6	7.4	22.8	1.5	0.9	0.9	b.d	0.8	65.1	100.0
	4	b.d	b.d	6.8	30.1	1.1	1.3	0.6	b.d	0.6	59.6	100.0
	5	b.d	b.d	6.9	21.5	1.2	0.6	0.4	b.d	0.6	68.9	100.0
	6	b.d	b.d	6.7	21.1	1.0	0.7	0.6	0.5	0.6	68.8	100.0
	7	b.d	0.7	6.9	20.9	1.3	0.5	0.8	b.d	0.6	68.4	100.0
	8	b.d	b.d	6.8	21.8	1.5	0.9	0.7	b.d	0.7	67.7	100.0
	9	b.d	b.d	7.7	22.8	1.3	1.0	0.6	b.d	0.9	65.6	100.0
	10	b.d	b.d	7.4	22.5	1.2	0.9	0.6	b.d	0.6	66.8	100.0
	11	b.d	b.d	6.7	21.0	1.2	0.8	0.7	b.d	0.7	68.9	100.0
	12	b.d	0.7	7.4	22.9	1.6	1.1	0.7	0.5	0.6	64.5	100.0
	mean	b.d	0.7	7.0	22.6	1.2	0.8	0.6	0.5	0.7	66.7	100.9
ACC 8	1	0.5	0.9	2.4	16.1	b.d	0.8	1.0	b.d	0.4	77.9	100.0
	2	b.d	1.0	1.4	10.4	b.d	0.6	1.3	b.d	b.d	85.4	100.0
	3	b.d	1.0	1.4	9.8	b.d	0.8	1.2	b.d	b.d	85.8	100.0
	4	b.d	0.7	2.7	17.1	0.4	0.9	2.0	b.d	b.d	76.3	100.0
	5	b.d	0.7	3.0	22.3	0.5	1.7	2.7	b.d	b.d	69.2	100.0
	6	b.d	0.9	1.1	6.9	b.d	0.5	0.8	b.d	b.d	89.9	100.0
	7	b.d	0.8	1.6	10.0	b.d	0.5	1.0	b.d	b.d	86.1	100.0
	mean	0.5	0.9	1.9	13.2	0.4	0.8	1.4	b.d	0.4	81.5	101.1

APPENDIX B: TRANSITIONAL SITES FULL CHEMICAL DATA

ROSE COTTAGE, DYMOCK (RCD)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
RCD 37 1	1	0.6	1.0	5.6	25.5	0.9	1.5	3.8	b.d	0.3	60.9	100.0
	2	0.5	0.7	5.9	25.0	0.6	1.9	3.4	b.d	b.d	61.9	100.0
	3	b.d	1.2	4.3	19.9	0.5	1.2	2.0	b.d	b.d	70.9	100.0
	4	b.d	1.2	3.5	19.6	b.d	0.9	2.2	b.d	b.d	72.7	100.0
	5	b.d	1.0	4.2	18.4	b.d	1.3	2.0	b.d	b.d	73.0	100.0
	6	0.6	1.0	4.6	20.9	b.d	1.3	2.5	0.3	b.d	68.8	100.0
	7	b.d	0.9	4.6	20.1	0.6	1.3	2.3	b.d	0.4	69.9	100.0
	8	0.6	0.8	4.4	18.3	0.6	1.3	2.7	b.d	b.d	71.3	100.0
	9	b.d	1.0	4.5	20.0	b.d	1.4	2.5	b.d	b.d	70.6	100.0
	10	0.5	1.0	4.8	20.8	b.d	1.2	2.7	b.d	b.d	69.0	100.0
	11	0.8	0.9	5.1	22.3	0.6	1.3	2.9	b.d	b.d	66.1	100.0
	12	b.d	0.8	4.7	18.8	0.5	1.1	2.4	b.d	b.d	71.8	100.0
	13	0.5	0.9	4.6	19.5	b.d	1.2	2.7	b.d	b.d	70.7	100.0
	mean	0.6	1.0	4.7	20.7	0.6	1.3	2.6	0.3	0.4	69.0	101.1
RCD 32 1	1	b.d	1.1	4.7	23.0	0.8	1.9	4.8	b.d	b.d	63.7	100.0
	2	0.5	1.2	4.7	23.2	0.8	1.9	5.0	b.d	b.d	62.8	100.0
	3	b.d	1.0	4.4	21.8	0.7	1.8	4.5	b.d	b.d	65.8	100.0
	4	b.d	1.0	4.4	21.6	0.8	1.8	4.5	b.d	b.d	66.0	100.0
	5	0.6	1.0	4.6	22.5	0.6	1.9	4.7	b.d	b.d	64.1	100.0
	6	0.4	1.0	4.6	22.5	0.8	1.9	4.7	b.d	b.d	64.1	100.0
	mean	0.5	1.0	4.6	22.4	0.7	1.9	4.7	b.d	b.d	64.4	100.3
RCD 15 5	1	0.5	1.0	5.7	27.9	0.8	2.2	4.1	b.d	b.d	57.9	100.0
	2	0.7	1.1	5.9	27.7	0.6	2.2	4.6	b.d	b.d	57.3	100.0
	3	0.5	1.2	5.3	27.6	0.8	2.3	4.3	b.d	b.d	58.0	100.0
	4	0.5	1.1	5.6	26.4	0.7	2.3	4.4	b.d	b.d	59.0	100.0
	5	0.7	1.2	6.0	28.9	0.7	2.3	4.3	b.d	b.d	56.0	100.0
	6	0.5	1.4	5.5	27.9	0.6	2.3	4.1	b.d	b.d	57.7	100.0
	7	0.6	1.1	6.0	27.1	0.7	2.4	4.5	b.d	0.4	57.3	100.0
	8	0.6	1.1	5.7	27.2	0.8	2.4	4.5	0.5	b.d	57.4	100.0
	9	0.7	1.1	5.7	27.2	0.8	2.2	4.5	0.4	b.d	57.5	100.0
	10	0.6	1.2	5.2	26.4	0.7	2.1	4.3	b.d	b.d	59.5	100.0
	11	b.d	1.2	5.2	27.8	0.8	2.2	4.4	b.d	b.d	58.4	100.0
	mean	0.6	1.2	5.6	27.5	0.7	2.3	4.3	0.4	0.4	57.8	100.7
RCD 15 4	1	0.5	1.1	5.9	25.1	b.d	1.8	3.5	0.3	b.d	61.9	100.0
	2	0.5	1.1	6.0	24.7	0.6	1.8	3.5	0.3	0.4	61.1	100.0
	3	b.d	0.9	6.7	26.0	0.9	1.8	3.7	0.3	b.d	59.8	100.0
	4	b.d	1.1	6.1	26.3	0.6	2.0	4.0	b.d	0.3	59.6	100.0
	5	0.4	1.1	6.0	25.8	0.5	2.2	3.9	b.d	b.d	60.2	100.0

	6	b.d	1.2	5.5	25.9	0.4	1.9	3.9	b.d	b.d	61.2	100.0
	7	b.d	1.1	6.3	26.1	0.5	2.1	4.1	b.d	0.3	59.5	100.0
	mean	0.4	1.1	6.1	25.7	0.6	1.9	3.8	0.3	0.3	60.5	100.7
RCD 37 2	1	b.d	0.9	4.8	20.7	0.6	1.3	2.2	0.3	0.2	69.1	100.0
	2	0.3	0.9	5.1	20.9	0.6	1.4	2.3	b.d	0.3	68.2	100.0
	3	b.d	0.9	4.9	20.2	0.7	0.8	1.7	b.d	0.3	70.6	100.0
	4	0.4	1.0	4.7	18.1	0.7	1.3	2.2	b.d	b.d	71.7	100.0
	5	0.3	0.9	4.9	20.2	0.6	1.6	2.5	b.d	0.3	68.8	100.0
	6	0.3	0.9	5.1	19.7	0.5	1.5	2.6	b.d	0.3	69.0	100.0
	mean	0.3	0.9	4.9	20.0	0.6	1.3	2.2	0.3	0.3	69.6	100.4
RCD 80 2	1	b.d	1.3	5.5	24.4	b.d	2.2	4.2	b.d	b.d	62.4	100.0
	2	0.7	0.9	5.6	24.1	b.d	2.2	3.5	b.d	b.d	63.0	100.0
	3	b.d	1.0	5.5	24.1	b.d	2.0	3.6	b.d	b.d	63.8	100.0
	4	b.d	1.1	5.5	25.0	b.d	2.3	4.3	b.d	b.d	61.9	100.0
	5	b.d	1.1	5.3	22.8	b.d	1.8	3.4	b.d	b.d	65.7	100.0
	6	b.d	1.4	5.8	24.2	b.d	1.9	3.4	b.d	b.d	63.3	100.0
	7	b.d	1.1	5.7	22.6	b.d	1.8	3.5	b.d	b.d	65.4	100.0
	mean	0.7	1.1	5.6	23.9	b.d	2.0	3.7	b.d	b.d	63.6	100.6

DYMOCK SEWAGE WORKS (DSW)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
DSW 10351	1	0.7	1.1	3.8	21.9	1.3	1.8	3.7	b.d	b.d	65.6	100.0
	2	0.5	1.1	3.5	22.4	0.7	1.7	3.4	b.d	b.d	66.8	100.0
	3	0.8	0.7	4.9	26.1	1.9	2.0	4.0	b.d	b.d	59.6	100.0
	4	1.0	0.8	4.2	22.7	1.0	1.7	3.0	b.d	b.d	65.8	100.0
	5	0.7	0.9	4.7	22.2	2.0	1.9	3.8	b.d	b.d	63.8	100.0
	6	0.6	0.8	3.7	17.2	1.4	1.6	3.3	b.d	b.d	71.5	100.0
	mean	0.7	0.9	4.1	22.1	1.4	1.8	3.5	b.d	b.d	65.5	100.0
DSW 10641	1	b.d	0.7	2.8	16.0	b.d	1.7	6.2	b.d	b.d	72.8	100.0
	2	b.d	0.7	3.0	15.9	b.d	1.7	5.8	b.d	b.d	73.0	100.0
	3	b.d	0.7	3.0	16.3	0.7	1.6	5.5	b.d	b.d	72.2	100.0
	4	b.d	0.6	3.2	18.4	b.d	1.8	5.7	b.d	b.d	70.4	100.0
	5	b.d	0.9	3.0	16.5	0.8	1.6	6.5	b.d	b.d	70.7	100.0
	6	b.d	0.8	2.9	16.4	b.d	1.7	6.1	b.d	b.d	72.2	100.0
	mean	b.d	0.7	2.9	16.6	0.8	1.7	6.0	b.d	b.d	71.9	100.5

DSW 10353	1	b.d	1.1	4.0	20.4	0.5	1.2	1.6	b.d	b.d	71.3	100.0
	2	b.d	1.0	4.5	21.3	b.d	1.0	1.5	b.d	b.d	70.8	100.0
	3	b.d	0.8	4.4	21.3	0.4	1.3	1.9	b.d	b.d	69.9	100.0
	4	b.d	0.8	3.9	20.9	b.d	1.0	1.5	b.d	0.3	71.6	100.0
	5	b.d	0.8	4.2	21.3	0.5	1.0	1.5	b.d	b.d	70.7	100.0
	6	b.d	0.7	4.8	22.1	b.d	1.2	1.7	b.d	b.d	69.6	100.0
	7	b.d	1.0	4.7	23.4	0.6	1.3	1.7	b.d	0.3	66.4	100.0
	mean	b.d	0.9	4.3	21.5	0.5	1.1	1.6	b.d	0.3	70.0	101.0
DSW 10352	1	b.d	1.3	4.2	17.6	0.4	1.1	2.2	b.d	0.2	72.8	100.0
	2	b.d	1.1	4.3	17.5	0.6	1.2	2.3	b.d	b.d	73.1	100.0
	3	b.d	1.3	4.3	16.0	b.d	0.9	2.0	b.d	b.d	75.5	100.0
	4	b.d	1.3	4.4	15.4	0.8	0.9	2.0	b.d	b.d	75.1	100.0
	5	b.d	1.2	4.3	16.9	0.7	1.2	2.6	b.d	b.d	73.0	100.0
	6	b.d	1.1	4.3	18.1	0.6	1.3	2.3	b.d	b.d	72.3	100.0
	7	b.d	0.9	5.9	23.8	0.9	1.4	2.7	b.d	b.d	64.4	100.0
	mean	b.d	1.2	4.5	17.9	0.7	1.1	2.3	b.d	0.2	72.3	100.3
DSW 10392	1	b.d	1.1	4.5	17.4	0.5	1.2	2.3	b.d	b.d	72.9	100.0
	2	b.d	1.1	4.7	18.1	0.4	1.6	2.8	0.3	b.d	71.2	100.0
	3	b.d	1.2	4.4	17.5	0.4	1.6	2.7	b.d	b.d	72.2	100.0
	4	b.d	0.8	5.1	20.1	0.4	1.9	3.2	b.d	b.d	68.6	100.0
	5	b.d	1.1	4.6	18.2	0.5	1.6	2.8	b.d	b.d	71.2	100.0
	6	b.d	1.2	4.6	17.6	0.6	1.5	2.5	b.d	b.d	72.2	100.0
	7	b.d	1.0	4.9	18.6	0.4	1.6	2.6	b.d	b.d	70.9	100.0
	mean	b.d	1.1	4.7	18.2	0.5	1.6	2.7	0.3	b.d	71.3	100.2
DSW 10671	1	0.4	1.2	4.1	23.5	0.8	2.0	4.9	b.d	0.3	62.9	100.0
	2	0.5	1.1	4.5	22.9	0.8	2.0	5.1	b.d	0.3	62.9	100.0
	3	0.5	1.2	4.2	22.7	0.9	1.9	4.9	b.d	0.4	63.4	100.0
	4	0.5	1.2	4.1	23.1	0.8	2.1	5.3	b.d	0.3	62.7	100.0
	5	0.4	1.2	3.7	24.4	0.9	1.8	5.0	b.d	0.4	62.3	100.0

	6	0.4	1.2	4.0	23.5	0.9	2.0	5.0	b.d	0.4	62.8	100.0
	mean	0.5	1.1	4.1	23.4	0.8	2.0	5.0	b.d	0.3	62.8	100.0

STOCKBURY, KENT (STO)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
IW - 060 STO	1	b.d	b.d	4.9	26.5	1.9	1.1	2.8	b.d	0.6	62.2	100.0
	2	b.d	b.d	4.7	26.4	2.0	1.0	2.9	b.d	0.6	62.4	100.0
	3	b.d	b.d	5.2	25.8	1.8	1.0	2.7	b.d	0.4	63.2	100.0
	4	b.d	b.d	4.1	25.1	1.5	0.7	2.6	b.d	0.4	65.6	100.0
	5	b.d	b.d	5.6	26.5	2.0	1.2	3.1	b.d	0.7	61.0	100.0
	6	b.d	b.d	5.0	26.3	1.7	1.1	2.7	b.d	0.5	62.7	100.0
	7	b.d	b.d	4.7	26.6	1.9	1.0	2.7	b.d	0.6	62.6	100.0
	mean	b.d	b.d	4.9	26.1	1.8	1.0	2.8	b.d	0.5	62.8	100.0
IW - 061 STO	1	b.d	0.3	3.4	22.7	1.3	0.8	1.2	b.d	0.5	69.9	100.0
	2	b.d	0.3	3.2	24.6	1.1	0.6	1.1	b.d	0.5	68.7	100.0
	3	b.d	0.3	2.8	24.4	1.3	0.3	1.1	b.d	0.5	69.4	100.0
	4	b.d	0.4	2.9	24.6	1.2	0.2	1.1	b.d	0.4	69.2	100.0
	5	b.d	0.4	3.4	25.5	1.4	0.6	1.4	b.d	0.4	66.8	100.0
	6	b.d	0.4	3.0	24.2	1.2	0.3	1.1	b.d	0.4	69.4	100.0
	7	b.d	0.3	3.0	23.9	1.2	0.5	1.2	b.d	0.5	69.4	100.0
	mean	b.d	0.4	3.1	24.3	1.2	0.4	1.2	b.d	0.4	68.9	100.0
IW - 065 STO	1	b.d	0.4	6.8	26.2	2.1	1.4	3.3	b.d	0.5	59.3	100.0
	2	b.d	0.3	6.8	26.1	2.0	1.4	3.2	b.d	0.7	59.4	100.0
	3	b.d	0.4	7.1	26.4	1.9	1.4	3.3	b.d	0.6	59.0	100.0
	4	b.d	0.4	6.9	26.6	1.9	1.5	3.4	b.d	0.6	58.7	100.0
	5	b.d	0.4	7.0	26.8	2.0	1.5	3.6	b.d	0.6	58.0	100.0
	6	b.d	0.4	6.1	26.7	1.9	1.1	3.0	b.d	0.6	60.1	100.0
	7	b.d	0.5	6.7	26.7	2.0	1.5	3.5	b.d	0.6	58.6	100.0
	mean	b.d	0.4	6.8	26.5	2.0	1.4	3.3	b.d	0.6	59.0	100.0

APPENDIX C: ROMAN SITES FULL CHEMICAL DATA

WORCESTER CITY FOOTBALL, WORCESTER (WFC)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
WFC 463 2	1	b.d	1.3	6.9	32.4	b.d	0.8	1.9	b.d	b.d	56.8	100.0
	2	b.d	0.8	6.7	36.1	b.d	1.7	2.6	b.d	b.d	52.1	100.0
	3	b.d	0.7	6.6	34.9	b.d	1.5	2.3	b.d	b.d	54.0	100.0
	4	0.8	0.5	12.1	41.2	0.9	3.0	3.8	0.7	b.d	37.0	100.0
	5	b.d	0.8	7.3	36.2	b.d	1.7	2.6	b.d	b.d	51.4	100.0
	mean	0.8	0.8	7.9	36.1	0.9	1.7	2.7	0.7	b.d	50.2	101.9
WFC 352 5	1	0.6	1.4	5.4	29.9	0.7	1.6	2.1	b.d	b.d	58.3	100.0
	2	0.6	0.9	5.8	30.7	0.6	2.3	2.8	0.3	b.d	56.0	100.0
	3	0.9	1.2	6.0	29.3	0.8	1.3	1.8	b.d	b.d	58.8	100.0
	4	0.8	1.6	6.7	30.6	1.3	1.9	2.3	b.d	b.d	54.8	100.0
	5	b.d	1.3	4.8	29.3	0.8	2.2	2.8	b.d	b.d	58.3	100.0
	6	1.3	1.3	5.3	29.3	b.d	0.7	2.1	b.d	b.d	60.0	100.0
	7	0.7	1.6	5.6	29.9	0.6	2.1	2.6	b.d	b.d	56.9	100.0
	8	0.6	1.2	5.4	28.5	0.6	2.1	2.6	b.d	b.d	59.1	100.0
	9	0.6	1.0	6.0	29.5	b.d	2.6	2.9	b.d	b.d	57.5	100.0
	mean	0.8	1.3	5.7	29.7	0.8	1.9	2.5	0.3		57.7	100.5
wfc 352 2	1	0.6	0.9	7.9	30.5	0.9	3.1	3.7	b.d	b.d	52.4	100.0
	2	b.d	1.4	5.4	28.3		1.8	3.0	b.d	b.d	60.2	100.0
	3	0.5	0.9	7.3	29.2		3.2	3.2	b.d	b.d	55.6	100.0
	4	b.d	1.4	5.4	28.7		1.6	2.1	b.d	b.d	60.8	100.0
	5	0.6	1.4	5.5	26.5	0.6	1.7	1.9	b.d	b.d	61.8	100.0
	mean	0.6	1.2	6.3	28.6	0.8	2.3	2.8	b.d	b.d	58.1	100.7
Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
WFC 463 1	1	b.d	0.9	4.3	29.3	b.d	1.2	1.0	b.d	b.d	63.4	100.0
	2	0.4	0.8	6.9	36.9	b.d	2.0	1.6	b.d	b.d	51.5	100.0
	3	b.d	0.7	4.2	34.7	b.d	1.0	0.7	b.d	b.d	58.6	100.0

	4	b.d	0.6	5.8	33.3	b.d	1.6	1.3	b.d	b.d	56.6	100.0
	5	b.d	0.8	4.4	27.9	b.d	1.2	1.8	b.d	b.d	63.9	100.0
	6	b.d	0.6	4.1	28.5	b.d	1.1	2.4	b.d	b.d	63.3	100.0
	7	b.d	0.4	7.7	31.8	b.d	1.6	2.7	b.d	b.d	55.8	100.0
	8	b.d	0.7	4.8	28.2	b.d	1.1	2.3	b.d	b.d	62.9	100.0
	9	b.d	0.8	4.5	27.5	b.d	0.9	1.4	b.d	b.d	64.9	100.0
	mean	0.4	0.7	5.2	30.9	b.d	1.3	1.7	b.d	b.d	60.1	100.3
WFC 352 1	1	b.d	1.5	6.3	29.5	0.6	2.7	2.5	b.d	b.d	57.1	100.0
	2	0.5	0.7	8.3	32.2	0.8	3.6	3.7	b.d	b.d	50.3	100.0
	3	0.7	1.2	5.1	29.6	0.6	2.3	2.7	b.d	b.d	57.8	100.0
	4	0.5	1.5	5.1	28.1	0.5	1.9	2.6	b.d	b.d	59.8	100.0
	5	b.d	1.0	4.6	19.2	b.d	0.3	1.0	b.d	b.d	73.9	100.0
	6	0.5	1.2	5.9	27.7	0.6	2.2	2.5	b.d	b.d	59.8	100.3
	7	0.6	1.2	6.0	28.6	b.d	1.9	2.5	b.d	b.d	59.2	100.0
	8	b.d	1.7	5.6	25.5	0.9	1.0	1.0	b.d	b.d	64.3	100.0
	9	0.5	1.3	5.5	27.5	0.8	1.4	1.8	b.d	b.d	61.2	100.0
	10	b.d	1.1	2.8	19.1	0.9	0.3	0.9	b.d	b.d	75.0	100.0
	11	b.d	1.4	5.9	29.2	0.6	2.5	2.6	b.d	b.d	57.8	100.0
	mean	0.6	1.3	5.2	26.0	0.8	1.4	1.7	b.d	b.d	63.5	100.5
WFC 352 5.1	1	0.6	1.2	4.8	27.4	0.7	1.7	2.3	b.d	b.d	61.3	100.0
	2	b.d	1.3	5.8	29.0	0.9	2.2	2.7	b.d	b.d	58.2	100.0
	3	0.5	1.1	5.9	28.8	0.7	2.1	2.7	b.d	b.d	58.3	100.0
	4	b.d	1.4	5.7	28.5	0.8	2.3	2.6	0.4	b.d	58.4	100.0
	5	0.5	1.2	5.5	28.8	0.7	2.3	2.7	0.3	b.d	58.1	100.0
	mean	0.5	1.2	5.6	28.5	0.7	2.1	2.6	0.4	b.d	58.9	100.4
Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
WFC 352 5.2	1	0.8	1.4	5.9	28.6	1.5	1.0	2.2	b.d	b.d	58.7	100.0
	2	0.5	1.1	5.3	30.2	b.d	2.3	2.8	b.d	0.3	57.4	100.0
	3	0.7	1.2	5.8	31.2	b.d	2.0	2.6	b.d	b.d	56.5	100.0

	4	0.5	1.2	5.6	29.8	0.9	2.1	2.6	b.d	b.d	57.5	100.0
	5	0.8	1.3	5.9	29.0	0.9	1.6	2.4	b.d	b.d	58.1	100.0
	mean	0.7	1.2	5.7	29.7	1.1	1.8	2.5	b.d	0.3	57.6	100.7
WFC 352 6.1	1	0.7	1.4	5.3	27.4	0.9	1.9	2.5	b.d	b.d	60.1	100.0
	2	b.d	2.7	9.2	34.0	1.7	2.3	1.6	b.d	b.d	48.6	100.0
	3	b.d	1.4	5.6	27.6	0.6	2.2	2.8	b.d	b.d	59.9	100.0
	4	b.d	1.4	5.2	27.9	0.7	2.0	2.7	b.d	b.d	60.2	100.0
	5	0.4	1.4	4.1	25.6	0.9	1.4	2.0	b.d	b.d	64.3	100.0
	mean	0.6	1.6	5.9	28.5	0.9	1.9	2.3	b.d	b.d	58.6	100.3
WFC 352 6.2	1	0.5	1.3	4.9	29.9	b.d	1.7	2.5	b.d	b.d	59.2	100.0
	2	0.7	1.5	7.4	32.0	1.6	2.1	2.1	b.d	b.d	52.7	100.0
	3	0.6	1.2	5.3	26.3	0.6	1.8	2.5	b.d	b.d	61.7	100.0
	4	b.d	1.4	4.8	26.7	b.d	1.7	2.6	b.d	0.4	62.5	100.0
	5	0.5	1.4	4.8	25.3	b.d	1.6	2.4	b.d	b.d	64.0	100.0
	mean	0.6	1.4	5.4	28.0	1.1	1.8	2.4	b.d	0.4	60.0	101.1
WFC 376 3	1	1.5	1.2	3.5	22.8	b.d	0.7	1.1	b.d	b.d	69.3	100.0
	2	b.d	1.9	3.9	24.9	b.d	1.4	1.6	b.d	b.d	66.3	100.0
	3	1.0	1.2	4.2	22.1	b.d	1.2	1.5	b.d	b.d	69.0	100.0
	4	b.d	1.3	4.2	23.1	b.d	0.6	1.4	b.d	b.d	69.4	100.0
	5	b.d	1.2	4.4	22.3	b.d	1.4	1.5	b.d	b.d	69.1	100.0
	6	b.d	1.4	4.7	20.5	b.d	1.1	1.2	b.d	b.d	71.1	100.0
	7	b.d	1.0	3.7	19.6	b.d	0.9	1.4	b.d	b.d	73.5	100.0
	8	b.d	1.2	3.8	20.5	b.d	1.4	1.3	b.d	b.d	71.8	100.0
	9	b.d	0.9	4.0	23.6	b.d	1.5	1.6	b.d	b.d	68.5	100.0
	10	b.d	0.8	4.1	23.5	b.d	1.6	1.6	b.d	b.d	68.4	100.0
	11	b.d	b.d	4.9	22.3	b.d	1.3	1.8	b.d	b.d	69.6	100.0
	12	b.d	1.2	5.2	22.8	b.d	1.2	1.5	b.d	b.d	68.2	100.0
	13	b.d	1.0	5.5	24.6	b.d	2.3	2.0	b.d	b.d	64.7	100.0
	14	b.d	1.2	4.3	22.1	b.d	1.1	1.2	b.d	b.d	70.1	100.0

	15	b.d	1.3	3.8	20.5	b.d	1.0	1.1	b.d	b.d	72.3	100.0
	16	b.d	1.0	5.7	25.1	1.6	0.7	1.8	b.d	b.d	64.0	100.0
	mean	1.2	1.2	4.4	22.5	1.6	1.2	1.5	b.d	b.d	69.1	102.7
WFC 376 2	1	0.5	1.0	4.6	22.3	0.5	1.3	1.3	b.d	b.d	68.6	100.0
	2	0.7	1.0	4.1	20.7	0.8	0.4	1.2	b.d	b.d	71.2	100.0
	3	0.9	0.8	5.4	22.3	0.7	0.9	1.3	b.d	b.d	67.7	100.0
	4	0.7	1.0	4.8	22.7	0.6	0.9	1.2	b.d	b.d	68.1	100.0
	5	0.5	0.9	4.3	21.5	b.d	1.0	1.4	0.2	0.3	70.0	100.0
	6	b.d	1.1	3.8	19.6	0.3	1.1	1.4	0.2	0.2	72.3	100.0
	7	0.4	1.0	4.3	20.5	b.d	1.2	1.3	b.d	b.d	71.4	100.0
	mean	0.6	1.0	4.5	21.4	0.6	1.0	1.3	0.2	0.2	69.9	100.6
WFC 352 4	1	0.4	0.8	7.8	35.8	b.d	2.3	2.7	0.3	b.d	49.9	100.0
	2	0.4	1.1	5.5	27.3	1.7	1.9	0.6	0.3	b.d	61.4	100.0
	3	0.3	0.9	5.3	28.6	b.d	1.2	1.5	0.3	b.d	61.9	100.0
	4	b.d	1.0	5.8	32.6	b.d	1.6	1.7	0.3	b.d	57.0	100.0
	5	b.d	2.5	2.8	32.2	b.d	0.9	1.1	0.2	b.d	60.2	100.0
	6	0.4	1.0	5.9	34.7	b.d	1.5	1.7	0.2	b.d	54.6	100.0
	mean	0.4	1.2	5.5	31.9	1.7	1.6	1.5	0.3	b.d	57.5	101.5

BEAUPORT PARK, BATTLE (BP)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
BP 2	1	b.d	2.4	9.5	32.6	1.2	1.6	9.7	0.6	2.8	39.7	100.0
	2	b.d	2.6	9.9	32.6	1.2	1.7	9.9	0.6	3.0	38.6	100.0
	3	0.3	2.5	10.4	33.4	1.0	1.8	10.1	0.6	2.9	37.0	100.0
	4	0.3	2.7	10.1	34.1	1.1	1.8	9.7	0.6	2.8	36.7	100.0
	5	0.3	2.6	10.2	33.9	1.0	1.8	9.8	0.6	2.9	36.9	100.0
	mean	0.3	2.5	10.0	33.3	1.1	1.8	9.9	0.6	2.8	37.8	100.1
BP 3	1	b.d	2.4	9.7	30.6	0.9	1.5	4.1	0.6	2.0	48.1	100.0
	2	b.d	2.1	9.2	31.1	1.1	1.6	4.2	0.6	2.0	48.1	100.0
	3	0.4	2.1	9.5	31.0	0.8	1.4	4.1	0.5	2.1	48.0	100.0
	4	b.d	1.5	9.6	31.2	0.9	1.6	4.5	0.6	2.2	48.0	100.0
	5	b.d	1.9	9.3	31.9	0.9	1.5	3.9	0.5	1.9	48.3	100.0
	mean	0.4	2.0	9.5	31.1	0.9	1.5	4.2	0.6	2.0	48.1	100.3

REDDING'S LANE, STAUNTON (RDL)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
RDL 9041	1	b.d	1.1	4.2	29.6	b.d	1.8	2.4	b.d	b.d	61.0	100.0
	2	b.d	1.0	4.6	29.4	b.d	2.0	2.6	b.d	0.3	60.1	100.0
	3	b.d	0.9	4.5	29.5	b.d	2.1	2.5	b.d	b.d	60.6	100.0
	4	0.5	1.0	4.8	29.1	b.d	2.0	2.5	b.d	b.d	60.2	100.0
	5	0.6	1.0	4.5	29.9	b.d	1.7	2.3	b.d	0.4	59.5	100.0
	6	b.d	1.1	4.9	30.2	b.d	1.7	1.8	0.4	0.5	59.5	100.0
	7	b.d	1.3	4.4	30.2	b.d	1.6	2.4	b.d	0.4	59.8	100.0
	mean	0.5	1.1	4.5	29.7	b.d	1.8	2.4	0.4	0.4	60.1	100.9
RDL 9043	1	0.6	0.6	7.0	27.3	b.d	2.7	2.8	b.d	b.d	59.0	100.0
	2	0.5	0.5	5.4	22.2	b.d	1.6	2.5	b.d	b.d	67.3	100.0
	3	0.7	0.7	7.4	23.9	0.7	1.3	1.8	b.d	b.d	63.6	100.0
	4	b.d	0.7	7.7	27.5	b.d	3.1	1.6	b.d	b.d	59.5	100.0
	5	0.6	b.d	7.8	24.7	b.d	2.9	1.2	0.3	b.d	62.6	100.0
	6	b.d	0.6	5.5	21.3	0.5	0.5	1.2	b.d	b.d	70.4	100.0
	mean	0.6	0.6	6.8	24.5	0.6	2.0	1.8	0.3	b.d	63.7	100.9
RDL 6101	1	0.5	2.1	5.6	25.5	1.1	1.1	5.5	b.d	b.d	58.6	100.0
	2	2.2	4.8	23.5	1.0	1.0	5.2	0.4	b.d	b.d	62.0	100.0
	3	0.5	1.8	6.0	25.0	1.1	1.5	6.0	b.d	b.d	58.3	100.0
	4	b.d	2.6	4.4	24.2	1.0	1.1	4.8	b.d	b.d	61.9	100.0
	5	b.d	3.3	4.2	25.0	0.7	0.8	4.2	b.d	b.d	61.8	100.0
	6	0.5	1.9	6.5	24.5	1.4	1.0	5.6	b.d	b.d	58.6	100.0
	7	b.d	2.7	5.3	25.2	0.9	1.3	5.1	b.d	b.d	59.5	100.0
	mean	0.9	2.7	7.9	21.5	1.0	1.7	4.5	b.d	b.d	60.1	100.4
RDL 7192	1	b.d	1.6	7.9	26.3	0.9	2.3	3.7	b.d	b.d	57.3	100.0
	2	b.d	2.0	8.0	27.6	0.7	1.9	4.1	0.4	b.d	55.4	100.0
	3	b.d	1.8	7.3	27.5	0.7	1.7	3.9	b.d	b.d	57.0	100.0
	4	b.d	1.8	8.4	28.1	0.9	3.2	4.6	b.d	b.d	53.2	100.0

	5	b.d	1.6	8.0	28.0	0.9	2.7	4.5	b.d	b.d	54.4	100.0
	6	b.d	1.5	8.9	29.2	0.9	3.2	5.0	b.d	b.d	51.2	100.0
	7	b.d	1.5	8.2	25.7	0.8	1.9	4.1	b.d	b.d	57.8	100.0
	mean	b.d	1.7	8.1	27.5	0.8	2.4	4.2	0.4	b.d	55.2	100.3
RDL 6022	1	b.d	b.d	1.1	15.5	4.1	b.d	1.4	b.d	1.2	76.6	100.0
	2	b.d	b.d	1.2	15.1	4.2	b.d	1.5	b.d	0.9	77.1	100.0
	3	b.d	b.d	1.9	15.2	5.7	b.d	2.3	b.d	0.7	74.2	100.0
	4	b.d	b.d	1.2	15.9	4.4	b.d	1.8	b.d	0.8	76.0	100.0
	5	b.d	b.d	0.9	17.2	4.6	b.d	1.7	b.d	0.8	74.8	100.0
	6	b.d	b.d	0.9	19.6	3.1	b.d	1.2	b.d	1.0	74.2	100.0
	7	b.d	b.d	1.4	16.7	5.1	b.d	1.7	b.d	0.9	74.2	100.0
	mean	b.d	b.d	1.2	16.4	4.5	b.d	1.7	b.d	0.9	75.3	100.0
RDL 6021	1	b.d	1.6	6.8	26.3	0.7	1.9	4.6	b.d	0.5	57.6	100.0
	2	b.d	1.5	7.3	27.0	0.7	2.1	5.0	b.d	0.6	55.9	100.0
	3	b.d	1.5	7.6	28.2	0.6	2.1	4.4	b.d	0.6	55.0	100.0
	4	b.d	1.4	8.2	28.4	0.7	2.0	4.2	b.d	0.8	54.3	100.0
	5	b.d	1.4	8.2	28.4	0.7	2.0	4.2	b.d	0.8	54.3	100.0
	6	b.d	1.5	7.7	28.1	b.d	1.7	3.9	b.d	0.6	56.5	100.0
	7	b.d	1.4	7.4	27.3	0.7	1.7	4.2	b.d	0.7	56.5	100.0
	mean	b.d	1.5	7.6	27.7	0.7	1.9	4.4	b.d	0.6	55.7	100.1

SHERRACOMBE FORD, DEVON (SHF)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
SHF1.1	1	b.d	b.d	7.8	35.1	0.6	1.1	0.6	0.3	0.9	53.6	100.0
	2	b.d	b.d	7.6	34.1	b.d	1.0	0.6	b.d	1.1	55.6	100.0
	3	0.5	b.d	8.2	38.7	0.5	1.1	0.7	0.4	1.0	48.9	100.0
	4	b.d	0.4	8.9	38.8	b.d	1.1	0.7	0.3	0.9	48.9	100.0
	5	0.5	b.d	7.8	34.2	b.d	1.1	0.7	0.3	1.0	54.4	100.0
	6	b.d	0.4	8.2	37.4	b.d	1.1	0.7	0.3	1.1	50.8	100.0
	7	b.d	b.d	8.5	36.1	0.6	1.3	0.7	0.4	1.1	51.4	100.0
	mean	0.5	0.4	8.1	36.3	0.6	1.1	0.7	0.3	1.0	51.9	101.0
SHF 2.1	1	b.d	b.d	6.3	27.7	b.d	1.4	0.8	0.3	b.d	63.6	100.0
	2	0.4	b.d	4.9	26.5	b.d	1.2	0.7	0.3	b.d	66.0	100.0

	3	0.6	b.d	5.9	28.0	b.d	1.4	0.8	0.3	b.d	63.0	100.0
	4	0.4	0.4	5.3	27.9	0.4	1.2	0.7	b.d	b.d	63.6	100.0
	5	0.4	b.d	4.9	27.1	b.d	1.1	0.7	b.d	b.d	65.8	100.0
	6	0.5	0.0	5.6	26.6	0.4	1.3	0.8	b.d	b.d	65.0	100.0
	7	0.5	b.d	5.4	26.6	b.d	1.3	0.8	0.3	0.3	64.9	100.0
	mean	0.5	0.2	5.5	27.2	0.4	1.3	0.8	0.3	0.3	64.6	100.9
SHF 3.1	1	b.d	b.d	5.0	28.0	0.6	0.8	0.4	0.2	0.4	64.6	100.0
	2	b.d	b.d	5.3	27.7	0.7	0.7	0.5	b.d	0.4	64.7	100.0
	3	b.d	b.d	5.3	28.2	0.6	0.9	0.4	b.d	0.5	64.2	100.0
	4	b.d	b.d	5.5	28.1	0.6	0.7	0.5	b.d	0.4	64.3	100.0
	5	b.d	0.3	5.5	29.1	0.6	0.8	0.4	b.d	0.4	62.8	100.0
	6	b.d	b.d	5.5	29.7	0.6	0.8	0.4	b.d	0.4	62.6	100.0
	mean	b.d	0.3	5.4	28.5	0.6	0.8	0.4	0.2	0.4	63.8	100.5
SHF 4.1	1	b.d	b.d	6.3	22.2	0.8	0.9	b.d	b.d	15.0	54.6	99.8
	2	b.d	b.d	6.7	22.8	1.1	1.1	0.3	b.d	14.5	53.5	100.0
	3	b.d	b.d	7.2	22.7	0.9	1.0	0.3	b.d	14.3	53.6	100.0
	4	b.d	b.d	6.9	22.7	0.9	1.1	0.3	b.d	14.7	53.3	100.0
	5	b.d	b.d	5.9	21.1	0.9	b.d	0.3	b.d	15.2	56.6	100.0
	6	0.8	b.d	6.4	21.6	0.8	1.1	b.d	b.d	15.0	54.4	100.0
	7	b.d	b.d	6.2	20.6	1.2	0.8	b.d	b.d	15.4	55.9	100.0
	mean	0.8	b.d	6.5	22.0	0.9	1.0	0.3	b.d	14.9	54.5	100.9
SHF 5.1	1	b.d	0.3	5.5	19.1	0.7	0.8	0.6	b.d	2.5	70.6	100.0
	2	b.d	b.d	4.2	20.8	1.0	b.d	0.5	b.d	3.5	70.0	100.0
	3	b.d	b.d	4.7	18.3	0.8	0.5	0.5	b.d	2.5	72.6	100.0
	4	b.d	0.4	4.8	20.1	0.6	0.4	0.5	b.d	3.3	69.9	100.0
	5	0.4	0.4	5.2	19.0	0.5	0.8	0.6	b.d	2.4	70.6	100.0
	6	b.d	0.4	5.2	22.4	1.0	0.2	0.6	b.d	3.7	66.5	100.0
	7	0.4	0.3	5.7	20.9	0.7	0.8	0.7	0.3	3.0	67.2	100.0
	mean	0.4	0.4	5.0	20.1	0.8	0.6	0.6	0.3	3.0	69.6	100.7

FEDERAL MOGUL, LYDNEY (FML)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
FML 37052	1	b.d	2.9	5.8	31.2	0.8	2.1	5.4	b.d	b.d	51.8	100.0
	2	b.d	1.0	8.5	31.7	1.0	3.0	7.2	0.4	b.d	47.2	100.0
	3	b.d	0.8	8.7	31.3	1.5	2.9	8.2	0.4	b.d	46.3	100.0
	4	0.5	1.4	7.9	30.6	1.3	2.5	7.0	0.3	b.d	48.5	100.0
	5	b.d	2.5	6.2	31.1	0.9	2.2	5.6	0.4	b.d	51.1	100.0
	6	b.d	1.8	7.3	32.2	0.8	2.7	6.8	b.d	b.d	48.4	100.0
	7	b.d	1.8	7.3	32.2	0.8	2.7	6.8	b.d	b.d	48.4	100.0

	mean	0.5	1.7	7.4	31.5	1.0	2.6	6.7	0.4	b.d	48.8	100.6
FML 44031	1	b.d	1.6	4.1	19.4	0.7	0.7	1.4	b.d	b.d	72.1	100.0
	2	b.d	1.8	4.7	18.6			0.7	b.d	b.d	74.2	100.0
	3	b.d		7.1	27.1	0.9	2.4	2.7	b.d	b.d	59.9	100.0
	4	0.9	1.8	5.2	24.1	0.8	0.8	1.8	b.d	b.d	64.8	100.0
	5	b.d	2.9	5.3	26.8	b.d	0.4	1.3	b.d	b.d	63.2	100.0
	6	b.d	2.0	4.4	20.5	b.d	b.d	0.6	b.d	b.d	72.5	100.0
	7	b.d	1.8	4.9	22.7	b.d	1.4	1.8	b.d	0.4	67.0	100.0
	8	b.d	1.5	5.0	19.8	b.d	1.1	1.7	b.d	b.d	71.0	100.0
	9	b.d	1.8	4.9	20.3	b.d	0.9	1.7	b.d	b.d	70.4	100.0
	10	b.d	1.5	4.3	20.0	b.d	1.1	1.9	b.d	b.d	71.2	100.0
	11	b.d	1.8	4.0	21.6	b.d	0.9	1.7	b.d	b.d	70.1	100.0
	12	b.d	1.8	5.2	19.6	b.d	b.d	0.9	b.d	b.d	72.5	100.0
	13	b.d	1.8	4.4	21.1	b.d	1.0	1.9	b.d	b.d	69.9	100.0
	mean	0.9	1.8	4.9	21.7	0.8	1.1	1.5	b.d	0.4	69.1	102.1
FML 44032	1	b.d	1.5	6.4	31.8	b.d	2.4	2.7	b.d	b.d	55.2	100.0
	2	b.d	2.9	4.9	30.0	b.d	0.7	1.5	b.d	b.d	60.0	100.0
	3	b.d	2.6	4.6	30.3	b.d	0.9	2.0	b.d	b.d	59.8	100.0
	4	b.d	1.6	7.6	32.0	b.d	2.5	3.0	b.d	0.4	52.9	100.0
	5	b.d	1.6	6.8	33.3	b.d	2.0	2.9	b.d	b.d	53.4	100.0
	6	b.d	1.1	9.4	35.0	0.9	2.1	5.5	0.6	b.d	45.3	100.0
	7	b.d	2.8	5.6	33.6	b.d	1.0	2.9	b.d	0.5	53.8	100.0
	mean	b.d	2.0	6.5	32.3	0.9	1.7	2.9	0.6	0.4	54.3	101.6
FML 37051	1	0.3	2.1	7.3	30.3	0.6	2.4	4.9	0.3	0.3	51.6	100.0
	2	b.d	2.0	6.7	28.1	b.d	2.0	3.8	0.3	b.d	57.1	100.0
	3	0.3	1.9	7.3	27.9	0.4	2.2	4.1	b.d	0.2	55.7	100.0
	4	0.4	1.8	7.8	30.7	0.4	2.3	4.6	0.3	b.d	51.6	100.0
	5	0.3	2.3	8.1	32.1	0.5	2.6	5.2	0.3	0.2	48.4	100.0
	6	0.4	2.5	7.9	31.9	0.5	2.6	5.0	0.3	0.3	48.8	100.0

	7	0.4	2.2	8.1	32.0	0.5	2.7	5.2	0.3	0.2	48.4	100.0
	mean	0.3	2.1	7.6	30.4	0.5	2.4	4.7	0.3	0.2	51.6	100.2
FML 44033	1	b.d	1.0	4.7	25.4	b.d	1.7	1.9	b.d	b.d	65.3	100.0
	2	b.d	1.1	4.3	24.3	b.d	1.4	1.6	b.d	b.d	67.4	100.0
	3	b.d	0.9	5.2	22.7	0.6	1.1	1.5	b.d	b.d	68.0	100.0
	4	b.d	1.0	4.5	24.3	b.d	1.4	1.6	b.d	b.d	67.1	100.0
	5	b.d	1.1	4.8	25.2	b.d	1.8	1.9	b.d	b.d	65.2	100.0
	6	b.d	1.0	5.1	25.6	b.d	1.4	1.7	b.d	b.d	65.2	100.0
	7	b.d	1.1	4.8	24.6	b.d	1.3	1.4	b.d	b.d	66.8	100.0
	mean	b.d	1.0	4.8	24.6	0.6	1.4	1.6	b.d	b.d	66.4	100.5

CLEARWELL QUARRY EXTENSION, LYDNEY (CQS 15)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
CQS 15 882	1	b.d	1.6	6.7	24.6	b.d	1.5	1.2	b.d	b.d	64.4	100.0
	2	b.d	1.6	6.7	24.6	b.d	1.5	1.2	b.d	b.d	64.4	100.0
	3	b.d	b.d	5.8	23.6	b.d	0.5	0.9	b.d	b.d	69.3	100.0
	4	b.d	1.0	6.5	24.6	b.d	0.5	1.1	b.d	b.d	66.3	100.0
	5	b.d	1.3	6.2	26.2	b.d	1.3	1.2	b.d	b.d	63.9	100.0
	6	b.d	1.1	6.4	23.5	b.d	0.5	1.1	b.d	b.d	67.5	100.0
	mean	b.d	1.3	6.4	24.5	b.d	1.0	1.1	b.d	b.d	66.0	100.2
CQS 15 881	1	b.d	2.0	6.7	25.9	b.d	1.6	4.6	b.d	b.d	59.1	100.0
	2	b.d	1.6	6.8	26.4	b.d	1.4	4.5	b.d	b.d	59.3	100.0
	3	b.d	2.0	6.5	27.8	b.d	1.6	4.9	b.d	b.d	57.1	100.0
	4	b.d	1.7	6.7	27.9	b.d	1.3	4.8	b.d	b.d	57.6	100.0
	5	b.d	1.8	6.7	27.2	b.d	1.9	5.1	b.d	b.d	57.4	100.0
	6	b.d	1.5	6.2	25.9	b.d	2.0	5.0	b.d	b.d	59.5	100.0
	7	b.d	1.7	6.5	26.6	0.9	2.1	4.7	b.d	b.d	57.5	100.0
	mean	b.d	1.8	6.6	26.8	0.9	1.7	4.8	b.d	b.d	58.2	100.8
CQS 15 874	1	b.d	1.3	4.1	18.7	b.d	0.9	1.5	b.d	b.d	73.5	100.0

	2	b.d	1.1	4.4	19.4	b.d	1.3	1.7	b.d	b.d	72.2	100.0
	3	b.d	1.4	3.9	20.0	b.d	1.2	1.5	b.d	b.d	72.0	100.0
	4	b.d	1.4	3.5	18.3	b.d	1.0	1.5	b.d	b.d	74.2	100.0
	5	b.d	1.4	3.5	19.1	b.d	1.2	1.7	b.d	0.4	72.8	100.0
	6	b.d	1.4	3.1	18.3	b.d	0.9	1.3	b.d	b.d	75.0	100.0
	7	b.d	1.3	4.0	18.7	b.d	1.2	1.5	b.d	b.d	73.3	100.0
	mean	b.d	1.3	3.8	18.9	b.d	1.1	1.5	b.d	0.4	73.3	100.4
CQS 15 873	1	b.d	1.5	5.6	24.2	0.5	1.2	2.6	b.d	0.4	64.0	100.0
	2	b.d	1.4	5.9	25.2	b.d	1.7	2.7	b.d	0.3	62.9	100.0
	3	b.d	1.5	5.9	24.7	b.d	1.5	2.8	b.d	0.4	63.3	100.0
	4	b.d	1.5	5.8	25.6	b.d	1.7	2.6	b.d	0.3	62.6	100.0
	5	0.4	1.6	5.9	25.4	0.4	1.9	3.0	b.d	0.3	61.2	100.0
	6	b.d	1.4	5.6	25.7	b.d	1.6	2.9	0.3	0.4	62.2	100.0
	7	b.d	1.4	5.6	25.6	b.d	1.5	3.0	b.d	b.d	62.8	100.0
	mean	0.4	1.5	5.8	25.2	0.5	1.6	2.8	0.3	0.3	62.7	101.0
CQS 15 885	1	b.d	1.5	5.5	23.8	0.6	1.7	3.8	b.d	0.4	62.7	100.0
	2	b.d	1.6	6.4	26.4	0.6	2.0	5.3	b.d	b.d	57.9	100.0
	3	b.d	1.5	6.0	26.7	0.9	1.7	5.0	0.4	0.4	57.3	100.0
	4	b.d	1.7	5.9	25.7	0.6	1.4	4.1	b.d	b.d	60.6	100.0
	5	b.d	1.6	5.9	24.9	0.5	1.7	4.4	b.d	b.d	61.1	100.0
	6	b.d	1.6	5.8	26.8	0.8	2.0	5.1	b.d	0.4	57.5	100.0
	mean	b.d	1.6	5.9	25.7	0.7	1.8	4.6	0.4	0.4	59.5	100.6

BRADENHAM FIELDS, BRADENHAM (BRAD)

Sample	#	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	total
BRAD 1018 7	1	b.d	b.d	4.9	25.4	0.7	0.7	1.1	b.d	0.6	66.6	100.0
	2	0.5	0.4	4.2	25.5	0.5	0.5	0.9	b.d	0.6	66.8	100.0
	3	b.d	b.d	5.1	26.3	0.7	0.8	1.1	b.d	0.5	65.6	100.0
	4	b.d	b.d	4.9	25.4	0.7	0.7	0.9	b.d	0.7	66.9	100.0

	5	b.d	b.d	5.2	25.2	0.7	0.6	1.0	b.d	0.8	66.5	100.0
	6	b.d	b.d	4.9	25.2	0.7	0.7	1.2	b.d	0.5	66.8	100.0
	7	0.5	b.d	4.9	25.4	0.7	0.7	1.2	b.d	0.6	66.0	100.0
	mean	0.5	0.4	4.9	25.5	0.7	0.7	1.1	b.d	0.6	66.5	100.7
BRAD 10184	1	b.d	b.d	4.7	26.2	0.6	0.5	0.9	b.d	0.7	66.6	100.0
	2	b.d	b.d	4.6	25.3	0.6	0.6	1.0	b.d	0.4	67.5	100.0
	3	b.d	b.d	4.3	25.8	0.6	0.6	0.8	b.d	0.6	67.4	100.0
	4	0.4	b.d	4.2	26.0	0.8	0.4	0.8	b.d	0.6	67.1	100.0
	5	b.d	b.d	5.2	27.2	0.6	0.7	1.0	b.d	0.5	64.9	100.0
	6	b.d	b.d	4.9	27.2	0.7	0.7	1.0	b.d	0.5	65.0	100.0
	7	b.d	b.d	4.3	26.9	0.5	0.4	0.8	b.d	0.5	66.5	100.0
	mean	0.4	b.d	4.6	26.4	0.6	0.5	0.9	b.d	0.5	66.4	100.3
BRAD 10077	1	b.d	b.d	5.5	24.4	0.6	1.3	1.9	b.d	0.3	66.0	100.0
	2	b.d	b.d	5.5	23.9	0.6	1.2	1.8	b.d	0.3	66.7	100.0
	3	b.d	b.d	5.9	24.0	0.6	1.3	1.9	b.d	b.d	66.4	100.0
	4	b.d	b.d	5.7	23.4	0.6	1.3	1.9	b.d	b.d	67.2	100.0
	5	b.d	b.d	5.1	23.1	0.6	1.1	1.7	b.d	b.d	68.5	100.0
	6	b.d	0.3	5.4	23.4	0.8	1.1	1.7	0.3	0.4	66.7	100.0
	7	b.d	b.d	5.7	23.6	0.7	1.2	1.9	b.d	0.4	66.5	100.0
	8	b.d	0.5	4.3	21.1	0.9	0.3	1.0	b.d	0.3	71.7	100.0
	9	b.d	b.d	6.2	23.2	0.7	1.2	1.8	b.d	0.4	66.6	100.0
	mean	b.d	0.4	5.5	23.3	0.7	1.1	1.7	0.3	0.3	67.4	100.7
BRAD 10182	1	b.d	b.d	5.3	24.0	0.9	0.9	1.3	b.d	0.7	66.9	100.0
	2	b.d	b.d	6.0	24.4	0.9	0.9	1.4	b.d	0.8	65.6	100.0
	3	0.4	b.d	5.7	24.4	0.7	1.1	1.5	b.d	1.0	65.2	100.0
	4	b.d	0.4	5.5	25.1	0.7	1.0	1.5	b.d	0.9	64.8	100.0
	5	b.d	0.5	5.4	24.2	0.7	1.2	1.5	b.d	0.8	65.9	100.0
	6	b.d	b.d	5.6	24.2	0.9	1.0	1.5	0.3	0.8	65.7	100.0
	7	b.d	b.d	5.5	24.1	0.9	1.0	1.5	0.3	0.8	65.8	100.0

	mean	0.4	0.4	5.6	24.4	0.8	1.0	1.5	0.3	0.8	65.7	100.9
BRAD 10078	1	b.d	b.d	4.6	27.3	0.6	0.7	0.9	b.d	0.6	65.4	100.0
	2	b.d	b.d	4.9	27.7	0.5	0.6	0.9	b.d	0.6	64.8	100.0
	3	b.d	b.d	4.8	26.6	0.7	0.6	1.0	b.d	0.5	65.8	100.0
	4	b.d	b.d	4.0	26.3	0.6	0.4	0.8	b.d	0.6	67.2	100.0
	5	b.d	b.d	4.6	26.4	0.6	0.5	0.9	b.d	0.7	66.3	100.0
	6	b.d	0.4	3.9	26.5	0.6	0.4	0.9	b.d	0.5	66.8	100.0
	7	b.d	b.d	4.4	27.1	0.6	0.6	0.8	b.d	0.5	66.1	100.0
	mean	b.d	0.4	4.5	26.8	0.6	0.5	0.9	b.d	0.6	66.1	100.3