CHAPTER 3: IRON SMELTING

3.1 Introduction

This chapter investigates the first of the medieval and post-medieval industries to be studied, namely iron smelting and in particular the iron smelting sites which pre-date the blast furnaces of the post-medieval period. For the purposes of this research, these pre-blast furnaces will be described as "iron smelting furnaces", even though there has been a long-held view which pre-supposed that all medieval, and earlier, smelting furnaces were of a particular design and function, producing iron in the form of a bloom and known generically as "bloomery furnaces". This perception was principally as a result of excavations carried out in the mid-20th Century. Since then, field evidence has shown that this simplistic view is complicated by chronological and technological improvements to the smelting process, i.e. simple small-scale manually-powered furnaces being supplanted by substantial water-powered high-bloomeries which may be regarded as the precursors of blast furnaces (G. McDonnell pers. comm.). Used here, the term "iron smelting furnace" encompasses a range of furnace types and designs which pre-date blast furnaces. The purpose of this chapter is to obtain a better understanding of the magnetic characteristics of the activities associated with this industry and thus improve geophysical interpretation of the features found on an iron smelting furnace site.

3.2 A summary of the history of iron smelting

The iron smelting process and investigations into the iron working industry in various parts of Britain are well documented in the literature; several authors have described iron smelting in Britain, in terms of geographic location, chronology and technology (Cleere and Crossley 1985; Crew 1991; Crew and Crew 1995; McDonnell 1988, 1995a and b, in press; Schubert 1957; Tylecote 1986). Whilst Crossley (1981), Schubert (1957) and Tylecote (1990) give an account of the general history of iron smelting, there are several regional studies; for example, the Forest of Dean: Cohen (1954) and Walters (1999); Furness, Cumbria: Fell (1908); the Weald of Kent and Sussex: Cleere and Crossley (1985); Rockingham Forest, Northamptonshire: Bellamy *et al*. (2001) and Foard (2001); and North Yorkshire: McDonnell (1972 and in press) and Hayes (1978). For examples of a wider European perspective of iron smelting, the reader is directed to the publications of Nørbach (1997), Pleiner (2000) and Scott (1990).

Within the archaeological landscape, occurrences of iron smelting furnaces are widespread and varied. Geographically, there are many examples throughout Britain, such as in the Weald, the Forest of Dean, Northamptonshire, North Yorkshire and Cumbria. There is also temporal variation: iron smelting furnaces have been dated from the Iron Age through to the medieval/post medieval period. Examples are the Iron Age/ Romano-British sites at Roxby (Inman *et al.* 1985) and Levisham (Hayes 1978) on the North York Moors (although there are doubts regarding the dating of these two sites: G. McDonnell pers. comm.), and at Corby Prior’s Hall, Northamptonshire (Clelland and Batt 2006; Greenwood and Batt 2007); the 2nd Century AD sites of Ashwicken, Norfolk (Tylecote and Owles 1960) and Minepit Wood, Sussex (Money 1974); the Saxon sites at Stamford (Mahany *et al.* 1982), Ramsbury, Wiltshire (Haslam 1980) and Millbrook, Sussex (Tebbutt 1982); and the medieval sites in Bilsdale, N. Yorkshire (McDonnell 1972), in north-west Wales (Crew and Crew 1995), at Stanley Grange, Derbyshire (Challis 2002) and in Crawley, W. Sussex (Cooke 2001).

Two different methodologies have been used to produce metallic iron from its ores (McDonnell 1988, 1995a and b; Schubert 1957; Tylecote 1990). In the first of these methods, known as the direct process, metallic iron never becomes liquid and the product, the bloom, is malleable enough to be directly formed into objects by hot working. In the second method, the indirect process, liquid cast iron is produced which has to be further refined to make it malleable enough for hot working.

It has been generally held by many, including Schubert (1957) and Tylecote (1990), that iron was smelted in Britain using the direct process throughout prehistory and up towards the end of the medieval period. Historically, the indirect process is associated with the blast furnaces of the post-medieval and later periods. There is, however, evidence which suggests that liquid cast iron was produced during the Saxon period (Mack *et al*. 2000) and in locations such as Bilsdale, N. Yorkshire, at some time in the 12th to 15th Centuries (G. McDonnell pers. comm.). The charcoal-fuelled direct process was conducted on a small scale and in short run batches, due to the necessity of having to remove the bloom, the spongy mass of metallic iron and slag, from the furnace structure. At first, combustion air was admitted to the furnace via low-capacity, manually-operated bellows, producing furnace temperatures which only resulted in the formation of a bloom. However, there are indications from slag morphology to suggest that water-powered bellows were in use much earlier than originally thought, which allowed higher furnace temperatures to be achieved and liquid iron to be produced. High capacity water-powered bellows were still being used after the post-medieval period; so far only one example of a post-medieval water-powered smelting furnace has been excavated, at Rockley Smithies near Barnsley (Crossley and Ashurst 1968). Both the quality and quantity of iron production had improved throughout the medieval period; larger quantities of slag were tapped from the furnace during smelting, reducing the amount which had to be hammered out of the bloom on an anvil later, and the quantities of iron had been increased through the use of water-power for bellows and hammers (Crossley 1994, 154-156). There is evidence to suggest that there was a gradual change-over to large-scale iron production using the indirect process during the post-medieval period with the introduction of the charcoal-fuelled blast furnace; the blast furnace at Rievaulx is known to be in operation in the latter part of the 16th Century while Rockley Smithies ran until the early 17th Century (Crossley and Ashurst 1968).

3.3 Description of the iron smelting process

Since it is the focus of this research, the following is a brief description of the charcoal-fuelled iron smelting process in the medieval and post-medieval periods, including a summary of smelting site locations and operating temperatures.

3.3.1 The smelting process

To produce workable iron from ore, it is necessary to reduce the ore to metallic iron at the same time as removing the unwanted gangue material. The methods for doing so changed very little in Britain from Romano-British times to the late medieval period, being based on the furnace technology historically associated with the direct process.

Having been mined and stored until required, the ore was prepared for smelting by a beneficiation process which included washing, roasting and crushing (McDonnell 1995a). Roasting converted the ore to its oxide (haematite) form and increased the surface area of the ore particles through micro-cracking.

After preheating the furnace with charcoal, charging with the ore/charcoal mix would commence (Cleere and Crossley 1985, 43ff). The hot carbon monoxide produced in the combustion zone adjacent to the air inlet, the tuyere, moved up the furnace and came into contact with the descending ore, where it was converted into CO_2 leaving free iron in discrete metal particles. At the same time, fusion took place between the silica and alumina in the gangue material and part of the iron oxide in the ore, resulting in a liquid fayalitic slag which descended the furnace, separate from the metal (Cleere and Crossley 1985, 43ff; McDonnell 1995a; Pleiner 2000, 133ff). As the smelt progressed in the direct process, the bloom formed below the tuyere and the slag built up at the bottom of the furnace. The bloom grew until it started to interfere with the air blast through the tuyere, at which point the smelting stopped and the bloom was removed (McDonnell 1995a, b; Pleiner 2000, 136). The liquid slag, which contained wüstite (FeO), other iron oxides and possibly partially reduced ore, was tapped off occasionally into a tap channel or slag pit, where it solidified and was subsequently broken up and deposited away from the furnace on the slag heap in a randomly oriented fashion (Cleere and Crossley 1985, 43ff; McDonnell 1995a). Where higher temperatures were achieved through the use of higher air capacity water-powered bellows, liquid iron was produced and similarly tapped off into a channel or pit along with the liquid slag.

3.3.2 Location of iron smelting sites

Many iron smelting sites are found close to a source of water, e.g. the sites of Ewecote, Hagg End, Kyloe Cow Beck and Stingamires in Bilsdale, North Yorkshire, for use in the construction of the furnace, ore preparation and quenching the bloom and slag, and potentially for driving a waterwheel to power bellows; sites are also located near to sources of wood and ore. Bellamy (1986) suggests that in the Rockingham Forest area the smelting sites, whether Romano-British or medieval, were chosen for their proximity to the abundant supplies of wood for charcoal rather than the sources of iron ore; it is more economical in labour to take the ore to the wood than vice versa. Foard (2001) notes that the iron smelting sites were within 4km of the charcoal production sites. It is not unreasonable to assume that iron smelting sites were located similarly in other iron producing regions of Britain.

The main types of iron ore found in Britain are carbonate, haematite and limonite (Tylecote 1990, 124-125; Geddes 1991, 167-168). The carbonate ores are the most common, occurring in two forms: as nodules found in the Wealden series and in the Coal Measures, and as sedimentary deposits (siderite) in Northamptonshire, Lincolnshire, Oxfordshire and the Cleveland Hills; Bellamy *et al*. (2001) give a detailed description of the Northamptonshire ores, both ironstone and nodules. The haematite ores occur mainly in Cumbria, whilst the limonite deposits are found in the Forest of Dean and in South Wales. Bog ore is a deposit formed in conditions where iron-bearing surface water meets organic materials causing iron oxide to be precipitated out, and is widespread many parts of Britain. As Tylecote (1990, 124) states, there is no part of Britain where iron ore of some sort is not accessible.

3.3.3 Operating temperatures

Tylecote and Owles (1960) observe that the size and shape of the shaft furnace remains at Ashwicken suggested operating temperatures of 1200°C, temperatures which were known from experimental work carried out by Wynne and Tylecote (1958); similar temperatures were noted by Tylecote *et al.* (1971) during a series of later iron smelting experiments. Geddes (1991, 170) notes that iron can be reduced at 800°C, but 1150°C is required to liquefy the slag. Preliminary experiments by Albek *et al*. (1997) with a slag-tapping furnace indicated temperatures peaking around 1000°C, depending on the volume of air being admitted. The experimental iron smelting undertaken by Hjärthner-Holdar *et al*. (1997) suggests that furnace temperatures of 1000 to 1300°C are achievable. Pleiner (2000, 133-134) postulates that in the combustion zone of a 1m high shaft furnace, temperatures at the mouth of the tuyere could reach over 1400°C, while a few centimetres away they would decrease to around 1200 to 1300°C, falling away to around 500 to 350°C at top of the furnace. A maximum temperature of 1365°C was recorded in the combustion zone of the Rievaulx experimental furnace (see Chapter 10, section 10.2.3).

It should be noted that there is no single furnace temperature as the different reactions occur at different points within the structure. The reduction of the ore takes place above 800°C in the upper part of the furnace whilst slag liquation occurs at *c*. 1300°C near the base (McDonnell 1995a, b). During the operation of the Rievaulx experimental furnace (Chapter 10, section 10.2.3), furnace temperatures consistently achieved over 800ºC in the furnace zone above the tuyeres, i.e. above the combustion zone, and up to 1100ºC in the same zone in the majority of the smelting operations. Figure 3.1 illustrates the temperature contours within the furnace.

3.4 Physical description of an iron smelting site

A medieval/post-medieval iron smelting site consisted of an assemblage of specific functions which allowed the smelting operation to be carried out (Pleiner 2000, 57). The central feature was the furnace, whilst other features which were associated with the preparation and storage of raw materials (ore, charcoal, and clay for furnace construction and repair), ore roasting, and deposits of slag and dismantled furnace remains were located close by. Although little evidence of shelters and buildings, temporary or permanent, has been found, it is reasonable to assume that some form of shelter for the iron smelters, the raw materials and smelting structures would have existed. An example of what was interpreted as being the remains of wooden buildings is at Ramsbury (Haslam 1980). One feature of the iron smelting process which is unlikely to be found on a site is that of charcoal production; this function was usually carried out close to the source of wood and at some distance from the smelting sites.

Several authors have attempted to classify iron smelting furnaces and to establish a typology, among them Cleere (1972), Martens (1978) and Tylecote (1962 and 1987, 151-162). All classifications can only be based on the prevailing knowledge of excavated furnaces and as such no classification system can be complete (Pleiner 2000, 143). Based on construction styles rather than chronological sequences, Pleiner (2000, 145-194 and Fig. 73) categorises the principal forms of the iron smelting furnace into five types: bowl, slag-pit, domed, shaft and underground. McDonnell (2001) suggests that typologies in general are flawed and that smelting furnaces are all variations of the one type, i.e. the shaft furnace.

It is, therefore, difficult to describe precisely what an iron smelting furnace looked like, but it is useful to consider the furnace as a shaft with variations in height and diameter (McDonnell 1995b). The conventional notion of a "typical" furnace is of a cylindrical clay shaft between 1 and 2m in height, an internal diameter of 30 to 40cm (possibly up to 1m), and 15 to 20cm thick walls for supporting the fuel/ore charge and for insulation purposes (McDonnell 1995a); Figure 3.2 illustrates the reconstruction of two iron smelting furnaces, indicating typical furnace dimensions. There may be some distortion in the diameters and wall thicknesses due to re-lining of the lower part of the furnace around the combustion zone. Current opinion speculates that furnaces may be higher than originally thought, possibly up to 3m, based on excavation evidence from Bilsdale, North Yorkshire (G. McDonnell pers. comm.). Sloping away from the furnace towards the slag deposits is a tapping channel or slag pit into which the slag is allowed to run and solidify before being discarded.

One feature of a furnace structure which may occur in Britain for which there is little evidence is an insulating collar. Borup (1997) describes the Østland shaft furnace which was a characteristic feature of all medieval iron producing areas in south-eastern Norway. The basic dimensions of this furnace type were very similar to the experimental furnaces of Albek *et al*. (1997) and Joosten *et al*. (1997), i.e. around 90cm high with internal diameters of 30 to 40cm and wall thicknesses of 5cm, but there was a collar-like feature at the base of the furnace consisting of vertically-positioned flagstones which surrounded the shaft, with the space between the furnace wall and the stones filled with sand; Figure 3.3 shows a reconstruction. The purpose of this collar was to stabilise and insulate the furnace, as well as providing a platform which enabled the furnace to be charged.

The main components of a medieval/post-medieval iron smelting site, and the inputs and outputs of the process, are shown diagrammatically in the flow diagram of Figure 3.4.

3.5 Iron smelting residues

For the purposes of this research, iron smelting residues are defined as those associated with the iron smelting furnaces which pre-date blast furnaces and are the remains of the furnace structure and other features such as ore roasting areas, and the slags.

3.5.1 Structural remains

However they are classified, iron smelting furnaces are subject to normal archaeological formation processes. The variation in survival depends on initial construction; furnaces built into the sides of natural banks or clay platforms are much better preserved compared to free-standing furnaces. However, almost all of the furnace superstructure does not survive in the archaeological record, so the height of a furnace is speculative. Excavation evidence has shown that there can be too much damage for furnace design to be fully ascertained (Cleere and Crossley 1985, 100; Schubert 1957, 71ff; Pleiner 2000,143); for example, the survival of the archaeology on most of the Forest of Dean iron smelting sites was not sufficient to allow reconstruction of the furnace technology (Barber and Holbrook 2000).

The structural remains of iron smelting furnaces consist principally of that part of the furnace which was built into natural or man-made banking; it is extremely unlikely that any remains of surface-built furnaces still exist, their former presence being marked only by associated slag deposits. Figure 3.5 shows the iron smelting furnaces at Hagg End, Ewecote and Stingamires in various stages of excavation, indicating what remained of the furnace structures at these sites.

3.5.2 Remains of other features

Besides the furnace, the main feature to be found on a smelting site is the slag; this may be in the form of one or more heaps situated within a few metres of the furnace downstream of the tap channel. The size of the heaps vary depending on the amount of ore smelted and what remains in the archaeological record, from tens of kilos to several tonnes. The slag deposits can often be recognised by surface scatter of material on or close by site topographical features.

The remains of the other features associated with smelting, i.e. ore storage, roasting areas and charcoal storage, are not as readily identifiable. Some iron smelting sites had an adjacent area for roasting ore or for storing the roasted ore. These have often remained in an identifiable state in the archaeological record, as evidenced by extensive red deposits containing pieces of roasted ore, e.g. Brigstock Park, Northamptonshire (Bellamy 1986), or have been discovered through interpretation of magnetometer survey data, as at Stingamires, Bilsdale (see Chapter 8, section 8.3.1.2). Other ore roasting areas or platforms which have been identified are at Withyham (Sussex) (Money 1974) and Baysdale (N. Yorkshire) (Crossley 1981, 34). Charcoal storage is very difficult to identify, relying on the remaining scatter of charcoal pieces lying on an area of dark, charcoal-flecked soil.

3.5.3 Slags

Typically, iron smelting (pre-blast furnace) slag is dull black in colour, with surfaces showing slow, viscous flow either over other pieces of slag or over the tapping channel surface; there may be variations in surface sheen due to trace element concentrations. Slag may be dense or light in weight, depending on the porosity of the material. The size of slag can also vary considerably: tap slag may be small sized having been broken up as it flowed or was raked out of the furnace, in large blocks of porous material, or larger plano-convex cakes (furnace bottoms). As an example from the literature, Photos-Jones *et al*. (1998) give a description of the slag morphology typically found at the iron smelting sites in the Scottish Highlands. Initial visual examination of the slag deposits at the Kyloe Cow Beck iron smelting site in Bilsdale (Powell *et al*. 2002) had identified three morphological types, details of which can be found in Chapter 2, section 2.4.

3.6 Discovery and geophysical survey of iron smelting sites

Iron smelting sites have often been identified by field name and other documentary evidence (e.g. Bellamy *et al*. 2001), but usually by fieldwalking, when the quantity and distribution of slag or changes in soil coloration as a result of possible plough disturbance of slag deposits and ore roasting areas can be observed. Many furnace sites in the Rockingham Forest/Northamptonshire area have been exposed during quarrying (Bellamy *et al*. 2001) or through major road improvements (Jackson and Tylecote 1988); pipe laying revealed the middle-Saxon iron smelting site at Millbrook (Tebbutt 1982). Identification of sites may still be difficult as any visible remains may be sparse and restricted to topographical features only: furnace structures could have disintegrated over archaeological timescales or been removed, the quantities of surface slag material widely scattered, and there may not be much evidence of heat affected ground or stonework. Iron smelting furnaces which were built into natural or man-made banking have the greatest potential for magnetic enhancement of a site. Under all these circumstances, the optimum method of identifying sites is by the use of geophysical survey techniques (McDonnell 1995c).

Metal working sites have been geophysically surveyed mainly with proton and fluxgate magnetometers but also with earth resistance and magnetic susceptibility techniques for many years (Vernon *et al*. 1999). In Britain, most geophysical surveys have been carried out over iron working sites and a methodological approach has been developed for the geophysical survey of these sites (Vernon *et al*. 2002; Vernon 2004). (N.B. Iron working is defined as the overall process of producing iron goods, i.e. from smelting to smithing.)

There are many examples in the literature of geophysical surveys over iron working sites from different time periods. A magnetometer survey of Westhawk Farm (Kent) Romano-British settlement revealed two iron working workshops with both smelting and smithing areas (Paynter 2007): see Chapter 10, section 10.3.5 for details. The individual components of the late-Saxon smelting site at Cendry Holme in the Fineshade Valley, Rockingham Forest, i.e. furnaces and roasting hearths, were interpreted from the magnetometer survey data (Bellamy *et al*. 2001). Geophysical (magnetometer and earth resistance) surveys were undertaken at a number of medieval iron working sites in the Scottish Highlands, magnetometry in particular proving very useful in identifying the various features such as furnaces, anvils and slag deposits (Photos-Jones *et al*. 1998). Magnetometer, magnetic susceptibility and earth resistance surveys carried out over three medieval iron smelting sites in Bilsdale and Rievaulx, North Yorkshire, are evaluated by Vernon (1995) and Vernon *et al*. (1998a).

In geophysical prospection terms, the location of an iron smelting site could be significant with respect to the potential magnetic enhancement of the underlying soil mineralogy; where the iron oxide content of the soils and clays is relatively high then the operation of a furnace at the temperatures discussed in section 3.3.3 would result in significant magnetic enhancement to the extent that the magnetic anomalies produced would be easily recorded in a magnetometer survey. However, there are occasions when a magnetometer survey does not detect furnaces due to very low iron oxide content in some soils and clays. An example is the recent survey of a series of iron smelting furnaces at Corby Prior's Hall (Hall forthcoming).

Whatever the location, type or shape of furnace, or indeed whether a furnace produced a bloom or cast iron, in geophysical survey terms the magnetic anomaly or footprint of a furnace is essentially the same, i.e. a high positive value "core" of circular appearance surrounded by a "halo" of lower positive values. The overall size and shape of this footprint is dependent both on the temperature and duration of the smelting operation (the higher the temperature and the longer the duration, the greater the heat affected area) and the amount of heat affected material still remaining. It is probable that close by the furnace are one or more deposits of slag, the amount of which depends on the length of furnace operation and subsequent survival in the archaeological record; excavations at Kyloe Cow Beck, Bilsdale (Powell *et al*. 2002), showed that these slag deposits could be in the order of a few tonnes of material. It is possible that fuel (charcoal) storage and ore roasting areas are also nearby, but these are not so well defined geophysically as a furnace. Charcoal has no magnetic signature and storage areas are best detected by earth resistance survey. Roasting required temperatures of 600-800°C, but this bonfire-technology process does not necessarily result in a well defined magnetic signature like that of a smelting furnace and as such roasting areas may be more difficult to identify from geophysical magnetic survey data.

There can be problems detecting iron smelting sites by geophysical survey. Vernon *et al*. (2002) state that detecting the iron smelting furnace as a circular anomaly (or any other apparent shape) will depend on its original construction. Crew and Crew (1995) have surveyed several medieval iron smelting sites in north-west Wales using magnetometry and magnetic susceptibility survey methods, but experienced some difficulty with magnetometry due to the underlying igneous and metamorphic geology affecting the data recording; as a consequence magnetic susceptibility was the preferred technique (Vernon *et al*. 1998b).

3.7 Dating of iron smelting sites

Currently, one of the most important issues in the study of iron smelting is dating of the smelting sites. Dating can be difficult because there may be insufficient or unsuitable material remaining at a site. Often the slag deposits and furnace remains contain little or no diagnostic material culture, e.g. coins or pottery (Barber and Holbrook 2000), such that the only datable material is charcoal. Bellamy *et al*. (2001) describe sampling a number of slag patches and mounds for charcoal, and subsequently obtaining a series of radiocarbon dates for these sites, ranging from the 5th Century AD to the 13th Century. No pottery was discovered at any of the iron smelting sites in Bilsdale, North Yorkshire, where the author excavated during the period of this research and only one piece from the whole of the smelting site complex at Myers Wood, near Huddersfield, W. Yorkshire. The iron smelting site at Millbrook, Sussex, was dated to the 9th Century by a combination of associated pottery, archaeomagnetic and radiocarbon dating (Tebbutt 1982). A method has been developed whereby high value anomalies, recorded by a magnetometer survey and interpreted as smelting furnaces, are modelled as high amplitude dipoles with estimates of the direction of magnetisation for each dipole in terms of declination and inclination. These directions are then compared with the British archaeomagnetic calibration curve to derive the date of the last furnace operation (Crew 2002).

Since the operating temperatures noted above in section 3.3.3 are well above 700°C, there is a high probability of thermoremanence being achieved in the furnace linings and the heat affected clay material surrounding the furnace, and consequently dating of iron smelting furnaces by archaeomagnetic techniques is possible. In addition to Millbrook (Tebbutt 1982) noted above, archaeomagnetic dating has been undertaken on other iron smelting sites at Crawley, W. Sussex (Cooke 2001), Stanley Grange, Derbyshire (Challis 2002) and Corby Prior's Hall, Northamptonshire (Clelland and Batt 2006; Greenwood and Batt 2007).

All the iron smelting furnaces investigated in this research were dated archaeomagnetically using the method described in Chapter 2, section 2.6 and the reports are summarised in Chapter 8, section 8.3.

3.8 Iron smelting site investigations

Investigations into the process and residues of medieval/post-medieval iron smelting have been carried out along three linked paths: susceptibility measurements of selected samples of ore, roasted ore, slag and other iron smelting related material, including linear sampling of heat affected material associated with the smelting process; geophysical surveys of known iron smelting sites; and archaeomagnetic dating.

Whilst the quantity of iron smelting furnace slag available for sampling was not restricted, there being a plentiful supply from the adjacent slag heaps, the amount of material from the other sources noted above was considerably less, being a function of both the smelting process itself and the availability of material in the archaeological record, but this was still considered to be sufficiently representative for the comparative nature of the susceptibility analysis.

3.8.1 Laboratory measurements

Laboratory measurements of magnetic susceptibility were carried out on three specific groups: (a) samples of different types of material from iron smelting, blast furnace and other sites, (b) samples from heat affected surfaces associated with iron smelting furnaces and ore roasting areas, obtained by a linear sampling method, and (c) samples from the remainder material following preparation for archaeomagnetic dating, as defined in Chapter 2, section 2.6.

3.8.1.1 Site samples

The preparation and measurement procedure is described in Chapter 2, section 2.5. A total of 525 samples, in 6 categories and from 11 sites, were analysed:

(a) Ore: 26 samples from 5 sites (Bretton, Myers Wood, Rockley, Rosedale and Tankersley);

(b) Roasted ore: 50 samples from 4 sites (Bretton, Myers Wood, Rosedale and Stingamires);

(c) Iron smelting slag: 375 samples from 3 sites (Kyloe Cow Beck, Myers Wood and Stingamires);

(d) Blast furnace slag: 65 samples from 4 sites (Bretton, Rievaulx, Rockley and Sowerby Bridge);

(e) Iron smelting furnace in-fill: 3 samples from 2 sites (Myers Wood and Stingamires);

(f) Mined magnetite: 6 samples from 2 sites (Penoncilla (Spain) and Kamaishi (Japan)).

The location of the above sites and the method of sampling is as follows:

Bretton: random sampling of surface finds on the site of the Bretton blast furnace, within West Bretton Country Park, West Yorkshire;

Kyloe Cow Beck: selected samples from the excavation of the iron smelting site in Bilsdale, North Yorkshire;

Myers Wood: selected samples from the excavation of the iron smelting site near Kirkburton, Huddersfield, West Yorkshire;

Rievaulx: random sampling of surface finds around the public roads of the village of Rievaulx, North Yorkshire;

Rockley: random sampling of surface finds adjacent to the remains of the Rockley blast furnace near Birdwell, Barnsley, South Yorkshire;

Rosedale: random sampling of surface finds in the vicinity of Rosedale Chimney Bank, Rosedale, North Yorkshire;

Sowerby Bridge: random sampling of surface finds of blast furnace slag of unknown provenance and probably associated with road maintenance, Sowerby Bridge, West Yorkshire;

Stingamires: selected samples from the excavation of the iron smelting site in Bilsdale, North Yorkshire;

Tankersley: random sampling of surface finds of ironstone from Hugset Wood near Dodworth, South Yorkshire (donated by Dr. R. Vernon).

The mined magnetite samples were obtained and donated by Dr. R. Vernon, from random selection of surface finds at both of these two foreign mining sites.

The results of the susceptibility measurements for each category are shown in Tables 3.1 to 3.6 (derived from the calculations in the attached Appendices 1 to 15). A small number of the Myers Wood roasted ore and slag samples were not able to be measured for mass quadrature specific susceptibility using the PIM instrumentation (Chapter 2, section 2.5.3), either because they were marginally too large for the PIM measuring coil (although they did fit the A.C. Susceptibility Bridge) or they overloaded the instrument. It is considered that these unmeasured samples did not unduly affect the appropriate mass quadrature specific susceptibility and magnetic viscosity results.

Excluding two of the Bretton samples (BREO-B and BREO-D), the magnetic susceptibility values for the ore samples are low (shown in Table 3.1), ranging from 14 to 88 x 10^{-8} m^3 kg^{-1}, with an overall mean of 42 x 10^{-8} m^3 kg^{-1}. The corresponding magnetic viscosity range from 0.1 to 3.3% (mean 0.9%). It is possible that the two excluded Bretton samples are not ore but partially-roasted ore; they are morphologically similar to the other ore samples. Compared to the ore, the roasted ore samples have considerably higher values of magnetic susceptibility (Table 3.2). The mean value for the Bretton samples is *c*. 20400 x 10^{-8} m^3 kg^{-1}, Myers Wood *c*. 17800 x 10^{-8} m^3 kg^{-1}, Rosedale *c*. 2100 x 10^{-8} m^3 kg^{-1} and Stingamires *c*. 7100 x 10^{-8} m^3 kg^{-1}. Excluding the four Myers Wood samples under 2000 x 10^{-8} m^3 kg^{-1} increases the Myers Wood mean to *c*. 18500 x 10^{-8} m^3 kg^{-1}; similar to the Bretton ore samples above, these four samples could be partially-roasted ore. Overall, there is a magnetic viscosity range of 0.1 to 11.5% (mean 2.6%).

The magnetic susceptibility for all the iron smelting slag samples range from 47 to 61774 x 10^{-8} m^3 kg^{-1} (Table 3.3). Whilst the majority of the Kyloe Cow Beck and Stingamires samples (97% and 98% respectively) have susceptibility values less than 2000 x 10^{-8} m^3 kg^{-1}, 20% of the Myers Wood samples have susceptibilities greater than 2000 x 10^{-8} m^3 kg^{-1}. Excluding these values, the susceptibility range reduces to a maximum of 1978 x 10^{-8} m^3 kg^{-1}, with a corresponding mean of 526 x 10^{-8} m^3 kg^{-1}. The selection of the cut-off point of 2000 x 10^{-8} m^3 kg^{-1} was made on a subjective basis, i.e. the author took the view that on the evidence from Kyloe Cow Beck and Stingamires the susceptibility of iron smelting slag is typically less than 2000 x 10^{-8} m^3 kg^{-1}. As a consequence, the Myers Wood iron smelting slag samples were divided into two distinct susceptibility groups: low (< 2000 x 10^{-8} m^3 kg^{-1}) and high (> 2000 x 10^{-8} m^3 kg^{-1}). The individual mean values excluding the high values are 646 x 10^{-8} m^3 kg^{-1} (Kyloe Cow Beck), 514 x 10^{-8} m^3 kg^{-1} (Myers Wood) and 516 x 10^{-8} m^3 kg^{-1} (Stingamires). The mean of the Myers Wood high value susceptibilities is 12884 x 10^{-8} m^3 kg^{-1}. The overall range of magnetic viscosity is <0.1 to 8.9% (mean 1.0%). Excluding three Rievaulx and two Sowerby Bridge samples, which are all greater than 2000 x 10^{-8} m^3 kg^{-1}, the magnetic susceptibility values for the blast furnace slags (Table 3.4) are slightly lower than those of the iron smelting slags, ranging from 20 to 1955 x 10^{-8} m^3 kg^{-1}, with an overall mean of 273 x 10^{-8} m^3 kg^{-1}. The magnetic viscosity range for the corresponding number of samples is <0.1 to 4.9% (mean 0.5%).

Although there are only three furnace in-fill samples, all have very similar magnetic susceptibilities, i.e. a mean of 2371 x 10^{-8} m^3 kg^{-1} (Table 3.5); the magnetic viscosity mean value is 1.0%. The magnetic susceptibility range of the six mined magnetite samples is 53275 to 63800 x 10^{-8} m^3 kg^{-1} (Table 3.6), with a mean value of *c*. 56000 x 10^{-8} m^3 kg^{-1}; for comparison purposes, Hunt *et al*. (1995) quote a range of 20000 to 110000 x 10^{-8} m^3 kg^{-1}.

3.8.1.2 Linear sampling

Laboratory measurements of magnetic susceptibility were carried out on three groups of samples from heat affected surfaces, obtained by a linear sampling method: (i) a series of samples obtained at three iron smelting sites, (ii) a monoblock of material obtained from an ore roasting site, and (iii) a series of samples obtained at varying depths at an iron smelting site.

In each case, the sampling was carried out at set intervals or positions measured from (i) the remains of the furnace internal surface, (ii) the top surface of the monoblock, or (iii) the ground surface. The objective of sampling in this fashion was to determine the changes in magnetic susceptibility with distance, as a means of identifying the extent to which a particular process associated with iron smelting had magnetically enhanced the surfaces surrounding the process, both horizontally and vertically, and as a consequence of temperature or deposition of smelting process residues (see Chapter 7 for an assessment of magnetic susceptibility/temperature profiles).

3.8.1.2.1 Samples obtained by the linear sampling method

The measurement procedure is described in Chapter 2, section 2.5. A total of 72 samples, from four locations, were prepared for analysis:

(i) Samples obtained by linear sampling of working surfaces:

(a) Hagg End Trench 1: two sets of samples in N and SW directions at 10cm intervals (12 samples);

(b) Stingamires Trench 2: two sets of samples in N and NW directions at 5cm intervals (15 samples);

(c) Myers Wood Trench A: one set of samples at 10cm intervals (16 samples).

(ii) Samples obtained from the Stingamires Trench 1 monoblock:

(a) sub-soil layer A (4 samples);

(b) upper heat affected clay layer C (2 samples);

(c) lower heat affected layer D (4 samples);

(d) natural clay layer E (6 samples).

(iii) Samples obtained by depth sampling at Hagg End: Trench 2 (4 samples) and Trench 3 (9 samples).

In the first group, samples (a) and (b) were from two iron smelting sites in Bilsdale, and sample (c) from the ore roasting/charcoal production area of the iron smelting site near Huddersfield. The positions of the samples from each of the sites (a), (b) and (c) are shown in Figures 3.6 to 3.8.

The Stingamires Trench 1 material was a monoblock of heat affected layers and natural clay removed from a vertical section at the centre of the ore roasting area; the block size was 30cm long x 16cm wide x 10cm deep (Figure 3.9). Samples were removed using

2.5cm diameter by 2.5cm long plastic tubes normally used for archaeomagnetic dating sampling; the sample positions within each layer are shown in Figure 3.10.

Although not strictly linear sampling as applied at the Hagg End and Stingamires furnaces, samples were obtained at different depths in two trenches south of the Hagg End furnace, in areas of high valued magnetic anomalies apparent from the magnetometer survey (see section 3.8.2.2 below). The trench and sample locations are shown in Figure 3.11.

The results of the susceptibility measurements are shown in Tables 3.7 to 3.11 (derived from the calculations in the attached Appendices 16 to 20), and Figures 3.12 to 3.16. The majority of the linearly sampled susceptibility values are less than 1000 x 10^{-8} m^3 kg^{-1}, except where samples have been obtained from surfaces subjected to the effects of high temperatures, i.e. adjacent to the linings of the Hagg End and Stingamires iron smelting furnaces or within layers A to D of the Stingamires monoblock (Figure 3.10). The majority of the Hagg End susceptibility-with-depth values are below 2000 x 10^{-8} m^3 kg^{-1}, except in the upper layer (context 201) of Trench 2 where the samples were obtained from material which had been highly heat affected and derived from the smelting process.

3.8.1.3 Archaeomagnetic dating sample remainder material

Preparation of the archaeomagnetic dating (AMD) samples from five iron smelting sites – Ewecote, Hagg End, Kyloe Cow Beck and Stingamires (in Bilsdale, N. Yorkshire) and Myers Wood (near Huddersfield, W. Yorkshire) – resulted in sufficient remainder material (as defined in Chapter 2, section 2.6) being retrieved for magnetic susceptibility measurements to be made. A total of 344 remainder material samples, from the five sites, were prepared for analysis:

(a) Ewecote: Trench 2 iron smelting furnace (26 samples);

(b) Hagg End: Trench 1 iron smelting furnace (41 samples);

(c) Kyloe Cow Beck: iron smelting furnace (42 samples);

(d) Myers Wood: Trench A ore roasting/charcoal production area (24 samples);

(e) Myers Wood: Trench B iron smelting furnace context 207 (13 samples);

(f) Myers Wood: Trench B iron smelting furnace context 270 (21 samples);

(g) Myers Wood: Trench C slag deposits (38 samples);

(h) Myers Wood: Trench G iron smelting furnace (15 samples);

(i) Myers Wood: Trench L iron smelting furnace (21 samples);

(j) Myers Wood: Trench M iron smelting furnace (15 samples);

(k) Stingamires: Trench 1 ore roasting area (40 samples);

(l) Stingamires: Trench 2 iron smelting furnace (48 samples).

The magnetic susceptibility measurement procedure is described in Chapter 2, section 2.5, and the results are shown in Table 3.12 (derived from the calculations in the attached Appendices 21 to 32). For all the remainder material, the overall range of magnetic susceptibility is wide, from 66 to 15090 x 10^{-8} m^3 kg^{-1}, reflecting the variable amount of remanent material within the archaeomagnetic dating samples obtained from the 12 locations listed above. The corresponding magnetic viscosity values range from 0.2 to 9.1%.

3.8.1.4 Discussion

The results of the magnetic susceptibility measurements show that there is a wide range in the susceptibility of the slag and other smelting related material samples.

The range of magnetic susceptibility values for the ore samples is indicative of the iron oxide content and mineral form of the parent ironstone or other iron ore source. The Myers Wood, Bretton and Tankersley samples have higher mean susceptibilities than the Rosedale samples, reflecting the fact that the former samples are derived from the Coal Measures found in that part of South and West Yorkshire, whilst the Rosedale samples are from the Jurassic geological sequences. Whatever the source, the paucity of ore samples compared to iron smelting slag would result in a very low, even undetectable, magnetic anomaly during a magnetometer survey. Although a considerable quantity of roasted ore would have been produced for the smelting process, very little can be found in comparison to the volume of iron smelting slag. Roasted ore may have been regarded as a "precious" commodity, much time and energy having been spent on producing it in readiness for smelting, that very little would been wasted. Although the mean value of the susceptibility measurements listed in Table 3.2 is *c.* 17200 x 10^{-8} m^3 kg^{-1}, the small amounts of roasted ore remaining in the archaeological record could easily be missed during a geophysical survey when compared to the slag and other features of an iron smelting site.

The variations in mean values of susceptibility for the Kyloe Cow Beck, Myers Wood and Stingamires iron smelting slags (excluding sample values greater than 2000 x 10^{-8} m^3 kg^{-1}) (Table 3.3) is considered to be a function of both the sampling method and the effectiveness of the smelting process at these sites. Slag sampling is dependent on the volume of material remaining in the archaeological record at the time of excavation of the slag deposits, but the susceptibility variations are also indicative of how well the furnace was operated, i.e. how effective the smelting process was at producing a viable bloom, when around 50% of the original iron content in the ore could be lost to the slag (Crew 1991). In addition, it is conceivable for the slag composition to have varied during an individual smelting operation, irrespective of how effective the smelt was, due to variations in ore quality.

As noted above in section 3.8.1.1, the Myers Wood iron smelting slag samples were divided into two groups. The relatively high proportion of slag having susceptibilities greater than 2000 x 10^{-8} m^3 kg^{-1} may be due to the iron smelting process and specific investigations into the mechanism which results in these high values are beyond the scope of this research; the fact that there was so much high susceptibility slag would in itself have considerably affected the interpretation of the magnetometer surveys over the Myers Wood site (see section 3.8.2 below).

From research undertaken by Morton and Wingrove (1969) and built upon by many other studies including that of the Wealden Iron Research Group (2003), iron smelting slags contain a high proportion of iron oxide in the form of wüstite (FeO), as well as fayalite (Fe_2SiO_4 or $2FeO.SiO_2$) and a glassy phase which has a general composition based on CaO, Al_2O_3 and $2SiO_2$; the glassy phase was originally described as anorthite by Morton and Wingrove (1969), but has subsequently been shown to be incorrect as glassy phase compositions can vary considerably (G. McDonnell pers. comm.; see Chapter 9, section 9.4 for examples from this research). In contrast to iron smelting slags which contain 40 to 50%, and sometimes more, total iron oxide, blast furnace slag has only *c*. 2% iron oxide. In addition, blast furnace slag has a much higher silica (SiO_2) content, 50% or more compared to the 25 to 30% in iron smelting slags, and the total glassy phase content (CaO, Al_2O_3 and SiO_2) may be around 87%. Fayalite has a magnetic susceptibility of 5 to 130 x 10^{-8} m^3 kg^{-1} (Cornell and Schwertmann 1996: 155) and anorthite 0.1 x 10^{-8} m^3 kg^{-1} (Oder 1991). Consequently, the susceptibility of blast furnace slags would be expected to be substantially lower than that of iron smelting slags. However, the results of the susceptibility measurements carried out in this research show that the blast furnace slag has only slightly lower susceptibility than the iron smelting slag (Tables 3.3. and 3.4 statistical analyses), which suggests that the blast furnace slags may contain a higher than expected proportion of metallic iron, in the form of prills.

The measurements of the mined magnetite samples were undertaken so as to put into a wider context the susceptibilities of the ore, roasted ore and slags. As can be seen from Tables 3.3 and 3.6, the susceptibility of magnetite is two orders higher than the iron smelting slag susceptibility; thus only a small quantity of magnetite occurring in the slag (from incomplete ore reduction) can have a large effect on slag susceptibility and consequent magnetometer measurements.

The susceptibility measurements of the samples obtained by the linear sampling method at the Hagg End and Stingamires sites (Tables 3.7 and 3.8) produced results which are consistent with surfaces whose susceptibilities have been magnetically enhanced by high temperature iron smelting activity. The susceptibility results for the Myers Wood samples and the Stingamires monoblock samples (Tables 3.9 and 3.10) indicate surfaces or sections which have also been heat affected. (A comparison between linear sampling susceptibility/distance and susceptibility/temperature profiles is made in Chapter 7, section 7.5.) The decreasing susceptibility of the working surface with increasing distance from the furnace internal surface at Hagg End and Stingamires is indicated by the trendlines in Figures 3.12 and 3.13. The variations seen closer to the furnace are influenced initially by the availability of suitable sampling positions: the first 10cm in all four sampling directions were occupied by furnace lining material, and in the case of Hagg End SW sampling, this extended to 30cm. The first two NW samples at Stingamires are considered to be unreliable, probably as a result of contamination with lower susceptibility material such as slag. At Myers Wood Trench A ore roasting/charcoal production area, the linear sampling was carried out across a heat affected surface (Figure 3.8) and the susceptibility measurements clearly indicate the extent of magnetic enhancement along the line of the sampling. The trendline in Figure 3.14 identifies the location of the greater enhancement, which may have been the site of part of the ore roasting area. It is feasible that another set of linear samples to the north or south of the original line (Figure 3.8) would have also indicated the extent of the enhancement, but to a greater or lesser degree depending on the exact position of the ore roasting area. The Stingamires ore roasting area monoblock results illustrate the variation of susceptibility with depth, as a consequence of the application of heat (Figure 3.15). Here, the trendline shows a distinct reduction in susceptibility to 2000 x 10^{-8} m^3 kg^{-1} at 10cm depth, a further reduction to 1000 x 10^{-8} m^3 kg^{-1} by 14cm depth, thereafter reducing to a mean of 89 x 10^{-8} m^3 kg^{-1} (from Table 3.10) in Layer E, 18 to 30cm depth. The large change in susceptibility in the first 9cm, i.e. Layers A to C in Figure 3.10, is due to the effects of contamination by roasted ore giving way to the effects of high temperature from the ore roasting process. The susceptibility of the samples in Layer E (Figure 3.10) are considerably lower, indicating the depth to which the high temperatures have penetrated. The susceptibilities of the three samples at 23 and 26cm depths (E3 to E5) have a mean value of *c*. 20 x 10^{-8} m^3 kg^{-1}; sample E6 is considered to have been contaminated during the removal of the monoblock from the trench section.

The Hagg End Trenches 2 and 3 results (Figure 3.16) demonstrate the variation of susceptibility with depth, as a consequence of deposition of material associated with the smelting process, rather than with temperature. Since only two sets of samples were obtained from Trench 2, there is not as full a picture of the reduction of susceptibility with depth as the author would have wished when compared with Trench 3, but a clear change is seen, from a mean of *c*. 2150 x 10^{-8} m^3 kg^{-1} at 20cm depth to *c*. 1000 x 10^{-8} m^3 kg^{-1} at 40cm depth. It is possible that this reduction is coincidental with a change in the type of material that has been deposited in the area of Trench 2: for example, a layer of high susceptibility heat affected clay from the furnace structure which was being renewed overlaying a deposit of lower susceptibility material such as a mixture of clays and slag. Another possibility is that the high susceptibility layer contained the remnants of ore roasting activity which could have taken place in this location (Vernon 2004; see section 3.8.2.2 below). The profile from Trench 3 is a better representation of the susceptibility changes with depth. Two profiles can be seen in Figure 3.16: the first is based on the mean values of susceptibility of the four contexts in Trench 3, whilst the second is similar but excludes sample 302-1 (see statistical analysis in Table 3.11). The mean value of susceptibility for contexts 301 (931 x 10^{-8} m^3 kg^{-1}) and 302 (985 x 10^{-8} m^3 kg^{-1}, or 665 x 10^{-8} m^3 kg^{-1} excluding sample 302-1) compare favourably with the typical range of iron smelting slag susceptibility, being less than 2000 x 10^{-8} m^3 kg^{-1} (noted above in section 3.8.1.1). The reduction in susceptibility from 985 x 10^{-8} m^3 kg^{-1} (665 x 10^{-8} m^3 kg^{-1}) at 40cm depth to 134 x 10^{-8} m^3 kg^{-1} at 50cm, then to 53 x 10^{-8} m^3 kg^{-1} at 60cm is indicative of a change-over in the type of deposited material, i.e. from smelting process material to natural clay; although an apparent 60cm depth of deposit has been measured in Trench 3, it does not mean that there is the same depth over the whole of the area south of the furnace seen in Figure 3.11. It is feasible that the spatial distribution of the deposits is attributable to more than just the smelting process itself.

As discussed in Chapter 10, section 10.2.7 (in relation to the Rievaulx experimental iron smelting furnace), occasional flooding would have an effect on the spread and depth of the deposits due to the proximity of the Hagg End furnace site to a river (location details below in section 3.8.2.2); thus, the true (original) volume of the deposits is unlikely to be known, and the apparent shape of the deposits determined through geophysical survey is probably as a consequence of flooding incidents which have occurred since the site was abandoned. The wide variation in susceptibility at a depth of 20cm between the two sets of trench samples (Figure 3.16) suggests dissimilar material at that depth, but the close agreement in susceptibility at 40cm depth suggests the opposite. The results from Trenches 2 and 3 indicate the heterogeneous nature of the deposits in the immediate vicinity of the trenches, both spatially and in susceptibility. This parallels the findings at the Kyloe Cow Beck smelting site slag deposits where distinct variations in susceptibility were noted (Powell *et al.* 2002).

Of the 344 archaeomagnetic dating (AMD) remainder material samples measured, 43% came from the Myers Wood site, with the rest being split between the four Bilsdale sites of Ewecote, Hagg End, Kyloe Cow Beck and Stingamires. The samples were obtained from three groups of features: ore roasting areas, smelting furnaces and slag deposits (see section 3.8.1.3 for source details). The results in Table 3.12 indicate that there is a wide variation in susceptibility which is not site or group specific, i.e. there is no major distinction between the Bilsdale sites and Myers Wood. There is some similarity in the minimum values of susceptibility between the three groups of features, although not consistent across the sites. The range of susceptibility reflects the initial iron oxide content of the clays on or into which two of the features, ore roasting areas and furnaces, were built as well as the quantity of heat which was applied to the clays from the high temperature processes. The exception appears to be the slag deposits in Myers

Wood Trench C; here, the results show a very wide range in susceptibility of samples which were subsequently interpreted from the archaeomagnetic dating analysis, in section 3.8.3 below, as being fired clay and similar material from furnace remains deposited away from their original locations, mixed in with and contaminated by high susceptibility slag.

Similarities were anticipated when comparing the results of the susceptibility measurements of the AMD remainder material (Table 3.12) with the linearly sampled material at the Hagg End and Stingamires smelting sites (Tables 3.7 and 3.8), since the comparisons were to be made on the same type of material, i.e. the heat affected working surfaces surrounding the furnaces. The 16 Hagg End AMD remainder samples (Table 3.12: 135-10A to 135-18) have a mean susceptibility of 2651 x 10^{-8} m^3 kg^{-1} (range 573 to 8888 x 10^{-8} m^3 kg^{-1}) compared to the linear sample mean of 948 x 10^{-8} m^3 kg^{-1} (range 410 to 1729 x 10^{-8} m^3 kg^{-1}), and the 24 Stingamires AMD remainder samples (Table 3.12: T2-15A to T2-23D) have a mean susceptibility of 3392 x 10^{-8} m^3 kg^{-1} (range 1508 to 8374 x 10^{-8} m^3 kg^{-1}) compared to the linear sample mean of 1618 x 10^{-8} m^3 kg^{-1} (range 635 to 2391 x 10^{-8} m^3 kg^{-1}). However, as can be seen from these results there is a considerable difference between the AMD remainder material and the linear sample susceptibilities. These differences are indicative of the random nature of contamination of the working surface with roasted ore and slag; the method of preparation was the same for both groups of samples. Although the comparisons demonstrate that measuring the magnetic susceptibility of AMD remainder material appears to be unnecessary and superfluous to the susceptibility measurements of directly obtained working surface (linear) samples, these measurements have a use as a backup if there is insufficient directly obtained material.

The measured susceptibility ranges of the iron smelting related materials, i.e. ore, roasted ore, iron smelting and blast furnace slags, furnace in-fill, linearly sampled and AMD remainder material, are shown in Figure 3.17 in comparison with soils, natural clays and heat affected clays from iron smelting sites, and the mined magnetite samples. From this diagram, it can be seen that iron ore has a very similar susceptibility range to soils and natural clays, whilst all the other iron smelting related materials have sufficiently high susceptibilities to stand out against or contrast with the background susceptibility of the soils and clays. Although the susceptibility of the roasted ore samples is high, as only small quantities are expected to be found on iron smelting sites it is unlikely that the presence of roasted ore will make a significant impression on a magnetic geophysical survey. There are similarities between the measured susceptibility ranges of iron smelting slags (< 2000 x 10^{-8} m^3 kg^{-1}), heat affected clays, linearly sampled and AMD remainder material (from both furnace lining material and heat affected clay surfaces). Samples obtained by the linear sampling method are expected to have comparable susceptibilities to heat affected clay as these samples were taken from the working surfaces adjacent to the smelting furnaces; although the susceptibility range for all the AMD remainder material overlaps those of linearly sampled material and the heat affected clays, there is a considerable difference between the AMD remainder material samples from the working surfaces and the linearly sampled material susceptibilities, as noted in the previous paragraph. Iron smelting slags whose susceptibilities are greater than 2000 x 10^{-8} m^3 kg^{-1} are unusual for an iron smelting site; the high susceptibility is considered to be due to the greater quantities of metallic iron within the slag, compared to the slags typical of sites such as Kyloe Cow Beck or Stingamires, and may be indicative of the particular smelting operation at Myers Wood. The furnace in-fill material has a relatively high susceptibility, which is a consequence of the mixture of heat affected clays, slag and furnace lining material. The blast furnace slag, as measured in this research, has a wider range of susceptibility than expected. It was anticipated that the susceptibility would be low and comparable with lead slags (Chapter 4) and glass production residues (Chapter 5). However, it is considered that this wider range is due to the excess quantities of metallic iron within the slag as a consequence of the blast furnace process (the reasons are outside the scope of this research) but on this basis, magnetic geophysical surveys should be capable of identifying anomalies caused by blast furnace slag.

Comparison of the magnetic susceptibilities of iron smelting related materials, excluding blast furnace slags, indicates that a magnetic geophysical survey will be able to identify furnace features and slag deposits, even though these features contain a "mixture" of different materials; the survey will not be capable of distinguishing the individual materials.

3.8.2 Geophysical surveys

Magnetometer surveys were undertaken by Dr. Rob Vernon at Ewecote, Hagg End, Stingamires and Myers Wood, as part of a programme of geophysical surveys at these iron smelting sites, using a Geoscan FM36 fluxgate gradiometer; the author assisted with the surveys at Myers Wood. The magnetometer surveys at Ewecote, Hagg End and Myers Wood are described in detail in Vernon (2004). Separate volumetric magnetic susceptibility surveys were carried out by the author at Hagg End and Myers Wood only, using a Bartington MS2D field coil and a hand-held Psion data logger. Volumetric susceptibility surveys were considered at Ewecote and Stingamires but not carried out due to time constraints associated with the excavations. Figures 3.18 and 3.19 show the locations of the smelting sites.

3.8.2.1 Ewecote

A magnetometer survey was undertaken over six 20m x 20m grids at a resolution of 1m (1m intervals at 1m traverses), followed by a second over four 10m x 10m grids at 0.5m resolution (0.5m intervals at 0.5m traverses) centred on the high valued anomaly indicated near the centre of the 20m grid survey; the plots of both surveys are shown in Figure 3.20, the raw data being clipped to various ranges. The mean value of the raw data from the 20m grid survey is -1.8nT, the standard deviation 38nT, and the range -227 to 903nT: these positive and negative maxima are two separate single data values (singularities) approximately 8m apart. The corresponding raw data values from the 10m grid survey are 3.6nT (mean), 89nT (standard deviation) and -146 to 1173nT (range).

3.8.2.2 Hagg End

Eighteen 10m x 10m grids were surveyed by magnetometer at a resolution 0.5m (0.5m intervals at 0.5m traverses) over an area adjacent to the River Seph (Figure 3.18) which had previously been identified through fieldwalking as being a potential iron smelting site; the survey plot is shown in Figure 3.21 (upper). The raw data mean value is -0.4nT, the standard deviation 32nT, and the maximum positive and negative values are 609nT and -192nT. A further magnetometer survey was undertaken over four 5m x 5m grids at a resolution of 0.25m (0.25m intervals at 0.25m traverses) over an area of high data values (peak 609nT). The location of this second survey within the first survey area is indicated in Figure 3.21 (upper) and the survey plot is shown in Figure 3.21 (lower).The mean value of raw data is 10nT, the standard deviation 90nT, and the data range -106 to 765nT.

In addition to the two magnetometer surveys, a magnetic susceptibility survey was undertaken over 14 5m x 5m grids at a resolution of 0.25m (0.25m intervals at 0.25m traverses). The survey (Figure 3.22) covered the same area south of the furnace anomaly as the magnetometer surveys, which allowed a direct comparison to be made of the results from both survey techniques. The mean value of the raw data from the whole survey area is 233 x 10^{-5} [SI], the standard deviation 184 x 10^{-5} [SI], and the data range 9 to 7122 x 10^{-5} [SI]; this latter value is a single point assumed to be an isolated piece of ferrous material, coincident with a small cluster of positive data (peak 99nT) from the first magnetometer survey. Excluding this singularity, the data range reduces to a maximum of 1207 x 10^{-5} [SI]. The area south of the furnace anomaly identified by the magnetometer survey has a magnetic susceptibility data range of 40 to 1200 x 10^{-5} [SI] (mean *c.* 350 x 10^{-5} [SI]), with the majority of the data lying between 250 and 800 x 10^{-5} [SI], and corresponds to the slag deposits. The instrument overloaded at several data recording positions in the two grids in the north-west corner of the survey plot (Figure 3.22) due to the field coil recording the contamination caused by the excavated material from the furnace trench; "dummy" values were applied where appropriate (see Chapter 2, section 2.2.1).

3.8.2.3 Stingamires

An initial magnetometer survey was conducted over 15 10m x 10m grids at a resolution of 0.5m (0.5m intervals at 0.5m traverses); the survey plot is shown in Figure 3.23 (upper), the raw data being clipped to various ranges. The mean value of the raw data is 1.0nT, with a standard deviation of 40nT and a range of -231 to 873nT. A second magnetometer survey was carried out over four 5m x 5m grids at a resolution of 0.25m (0.25m intervals at 0.25m traverses) over two of the clusters of high value positive anomalies, indicated in Figure 3.23 (upper) (peak values 582nT and 873nT), as these were considered to be anomalies associated with furnaces. The location of these four grids with respect to the initial survey is highlighted in Figure 3.23 (upper) and the second survey plot is shown in Figure 3.23 (lower). The raw data mean is 7.4nT, the standard deviation 125nT, and the data range -256 to 937nT. The eastern cluster of high positive data (peak 937nT) has an associated cluster of lower value positive data (peak 240nT), whilst the western cluster (peak 845nT) stands alone.

3.8.2.4 Myers Wood

At the iron smelting site of Myers Wood, near Huddersfield, a total of 40 5m x 5m grids were surveyed by magnetometer at a resolution of 0.25m (0.25m intervals at 0.25m traverses), over an area which, as a result of fieldwalking and the extensive evidence of slag, suggested large scale smelting activity. A separate magnetometer survey was conducted over six 10m x 10m grids at a resolution of 0.5m (0.5m intervals at 0.5m traverses), over an area 15m to the north of the 5m grid survey. Both survey plots and their positions relative to the site datum line are shown in Figure 3.24. The mean value of the raw data from the 5m grid survey (Figure 3.24 lower block) is 1.6nT, the standard deviation 63nT, and the range -344 to 962nT. The corresponding data for the 10m grid survey (Figure 3.24 upper block) is -1.8nT, 10nT, and -97 to 154nT (respectively).

A magnetic susceptibility survey was carried out over 64 5m x 5m grids at a resolution of 0.25m (0.25m intervals at 0.25m traverses), over a similar area as the magnetometer surveys; this allowed a direct comparison to be made between the results from both survey techniques. The survey plot is shown in Figure 3.25, with the raw data clipped to various ranges. The mean value of the raw data from the whole survey is 418 x 10^{-5} [SI], the standard deviation 629 x 10^{-5} [SI], and the data range 0 to 9867 x 10^{-5} [SI]. The raw data statistics specific to the northern square area are 311 x 10^{-5} [SI], 188 x 10^{-5}

[SI], and 9 to 1016 x 10^{-5} [SI] (respectively). The majority of the data in this area lie in the range 400 to 600 x 10^{-5} [SI].

3.8.2.5 Discussion

The magnetometer surveys undertaken at Ewecote, Hagg End, Stingamires and Myers Wood are shown in Figure 3.26 superimposed with the interpretations of the principal magnetic anomalies (see Vernon 2004 for further details). The following is a brief description of the principal anomalies at each site compared with the excavation results.

The high valued anomaly in Figure 3.20, consisting of a cluster of positive data (peak value 903nT) near the centre of the Ewecote 20m grid survey, was interpreted by Vernon (2004) as a possible single iron smelting furnace with a tapping channel running south-east from it. Subsequent excavation of this anomaly revealed the remains of a partially disturbed furnace structure, heat affected clay surfaces, and a small quantity of burnt stone and ash (Figure 3.5). No significant amounts of slag were discovered, which substantiated the survey results: no magnetic anomalies were identified to the south or east of the furnace anomaly which could be interpreted as slag deposits.

The Hagg End 10m grid survey plot (Figure 3.21 upper) identified a cluster of positive data (peak 609nT) over which the 5m grid survey was conducted; this area was interpreted as a furnace. The 5m grid survey plot (Figure 3.21 lower) also shows a linear anomaly running north-east from the main anomaly and was interpreted as the tapping channel. The large area of weaker positive data to the south of the furnace anomaly, extending for approximately 18m with a maximum width of 10m, was interpreted as slag deposits. Excavation of the main anomaly revealed the remains of a well-preserved furnace structure built into a natural clay bank and surrounded by heat affected working surfaces, with the remnants of a tapping channel leading off in the direction indicated by the magnetometer surveys (Figure 3.5).

As Vernon (2004) states, although there is only one identified furnace at the Hagg End site, the surface and geophysical evidence would suggest that the site was the location for several other activities. Vernon (2004) speculates that a hollow or pit which had been found on the site to the south-east of the furnace may have been used for mining ironstone and as a source of clay. If the ore was mined *in situ* then it would have been roasted prior to smelting. The area between the furnace and the hollow might have been the location for this roasting activity. The cluster of positive magnetometer data contained in a 3m square area approximately 10m south-east of the furnace (Figure 3.21) could be indicative of the "magnetic remains" of ore roasting. However, the material excavated from Trench 2 (see section 3.8.1.2.1 above and Figure 3.11) did not contain evidence of roasted ore, even though there are similarities in the magnetic susceptibility results between the upper excavated layer of Trench 2 (context 201) (mean χ = *c.* 2150 x 10^{-8} m^3 kg^{-1}), the upper layers of the Stingamires Trench 1 ore roasting monoblock (mean χ = *c.* 2400 x 10^{-8} m^3 kg^{-1}) (see section 3.8.1.2.1 above and Figure 3.15) and the Stingamires Trench 1 ore roasting area archaeomagnetic dating remainder material (mean χ = *c.* 1700 x 10^{-8} m^3 kg^{-1}). The variation in susceptibility may be due to the different depths at which the samples were obtained in addition to the possibility of occasional flooding of the site, as noted in section 3.8.1.4 above and in Chapter 10, section 10.2.7).

From the Stingamires magnetometer survey plots (Figure 3.23), several high valued anomalies can be observed. Of these, the two which were further surveyed at 0.25m resolution, Figure 3.23 (lower), are highlighted in Figure 3.26. The western anomaly (peak 845nT) is apparently circular with a diameter of approximately 5m, and the eastern anomaly (peak 937nT) is also apparently circular but with a smaller diameter of around 2m. As stated above in section 3.8.2.3, the eastern anomaly has an associated cluster of lower value positive data (peak 240nT) about 2m to the east, whilst the western anomaly stands alone. There is a faint linear anomaly leading south-east from the eastern anomaly, and to the east and south-east of the western anomaly are two areas of relatively low value data. The initial interpretation was that both of the high value anomalies were furnace features, with the eastern anomaly having a tapping channel running south-eastwards and slag deposits to the east/south-east. Both anomalies were subsequently excavated. In Trench 1, the western anomaly was revealed to be an ore roasting area (Figure 3.27) and in Trench 2, a well preserved iron smelting furnace was uncovered (Figure 3.5) with traces of slag deposits at the eastern end of the trench. Due to time constraints this trench was not extended to discover the extent of the slag. Both trenches had sufficient heat affected material *in situ* for archaeomagnetic dating to be undertaken (see section 3.8.3 and Chapter 8). Although the other anomalies seen in Figure 3.23 are distinctive, excavation trenches put across them did not result in any specific features being identified.

The Myers Wood 5m grid magnetometer survey plot (Figure 3.24 lower block) indicates several distinct clusters of high value positive data, whilst in contrast, the 10m grid magnetometer survey (Figure 3.24 upper block) shows very few clusters of positive data. The 5m grid survey area was interpreted as complex site of iron smelting activity containing several furnace features and slag deposits, and the 10m grid survey area was initially interpreted as the site of charcoal production due to the abundance of surface charcoal and the charcoal-flecked nature of the soil. The site plan (Figure 3.28) shows the charcoal production area and the extent of the slag deposits across the whole site, as well as the location of the excavation trenches put in over the smelting activity features indicated by the geophysical surveys. Photographs of the charcoal production area (Trench A) and two of the furnace features (Trenches B and G) are shown in Figure 3.29. The clipped data ranges of ±50nT and ±20nT, in the bottom half of Figure 3.24, apply to both magnetometer surveys and demonstrate the relatively "quiet" magnetic characteristic of the charcoal production area in comparison with the main area of smelting activity to the south. In comparing the two survey techniques, it can be seen from Figures 3.24 and 3.25 that the magnetic susceptibility survey complements the magnetometer surveys in highlighting similar areas of magnetic anomalies across the site, particularly the more distinctive anomaly over the charcoal production area.

The Myers Wood site plan (Figure 3.28) also indicates the positions of the pits which were dug to obtain bulk samples of slag for metallographic, chemical and mineralogical analyses, as well as magnetic susceptibility measurements. A comparison is made between the 5m grid magnetometer survey data from a 1m square over each slag pit and the susceptibilities of the slag samples; the results are shown in Table 3.13. It can be seen that there is no direct correlation between the survey data peak readings and the mean susceptibility values, i.e. high survey data does not correspond to high susceptibility values. With the exception of SH4 and SH5 whose depths were not recorded at the time of excavation, each slag pit was 0.5m deep, i.e. at a known depth beneath the magnetometer. Therefore, the comparison suggests that the high value susceptibility slag lies towards the bottom of the slag pits, at a greater distance below the instrument, and in the case of SH3 probably at the bottom. In contrast, the higher value susceptibility material in the SH5 sample range is probably near the top. The outcome of this comparison is that the wide range in the slag deposit susceptibility values is unlikely to be detected by a magnetometer survey due to the variability in depth of the deposits. The high value susceptibility slag (> 2000 x 10^{-8} m^3 kg^{-1}) was concentrated into the slag deposits whose magnetic signature could be mistaken with that of remanent material from smelting furnaces; Vernon (2004) discusses a particular anomaly in Trench E (Figure 3.28), an arc of four distinct clusters of positive data, which was thought to represent the locations of potential furnaces but which on excavation were found to be concentrations of roasted iron ore and slag with roasted iron inclusions.

3.8.3 Archaeomagnetic dating of an iron smelting site

Archaeomagnetic dating of features at four iron smelting sites was undertaken during the period of this research: Ewecote, Hagg End and Stingamires (in Bilsdale, N. Yorkshire) and Myers Wood (near Huddersfield, W. Yorkshire). A fifth iron smelting site, Kyloe Cow Beck (also in Bilsdale), had been archaeomagnetically dated previous to this research (Powell *et al.* 2002).

3.8.3.1 Sampling and measurement procedures

A total of 18 iron smelting related features were sampled for AMD purposes (see Chapter 8 for details), oriented samples being obtained from furnace lining and heat affected clay material using the standard disc method described in Chapter 2, section 2.6. The direction of natural remanent magnetisation (NRM) of each sample was measured using a Molspin fluxgate spinner magnetometer (Chapter 2, section 2.6.1), and the characteristics of the magnetisation were investigated by the stepped alternating field (a.f.) demagnetisation of pilot samples, using the method described in Chapter 2, section 2.6.2. The majority of the samples had sufficient material left over from trimming to allow further magnetic analysis (i.e. mass specific susceptibility and magnetic viscosity measurements) to be carried out (see section 3.8.1.3).

As described in Chapter 2, section 2.6, the individual magnetic directions (declination and inclination) from each group of samples were entered into a Microsoft *Excel* spreadsheet (*ArchMag*) specifically designed to calculate the mean direction and its precision α_{95}. The stability of magnetisation of an individual sample was quantified by entering the magnetic directions (declination and inclination) measured at each stage of the a.f. demagnetisation process into another Microsoft *Excel* spreadsheet (*StabilityCalcs*) specifically designed for that purpose.

3.8.3.2 Dating of the measured magnetic direction

The stable, mean magnetic direction for each group of samples was corrected to Meriden (Chapter 2, section 2.6) and an archaeomagnetic date was then determined by visual comparison of the corrected direction with the British calibration curve in the conventional manner (Clark *et al*. 1988). All the archaeomagnetic dating attempted during the period of this research was undertaken using this calibration curve since the new software based on Bayesian statistical methods had not been published (Zananiri *et al*. 2007).

3.8.3.3 Discussion

The results of the AMD processing demonstrated that the majority of the sampled material was suitable for archaeomagnetic dating and did provide a record of the geomagnetic field at the time of the last cooling, but with some exceptions which are noted below. Reports were issued in all cases and are summarised in Chapter 8, section 8.3.1. Tables 8.1 and 8.2 summarise the results, including the comparative data for the iron smelting furnace at Kyloe Cow Beck.

All the features were successfully dated to the medieval period, with six exceptions. Of these, Ewecote Trench 1 (furnace feature) had a low level of precision (α_{95}) and could not be dated reliably, and five others - Hagg End Trench 1 (hearth feature), Myers Wood Trench B context 262, Myers Wood Trench C (groups B and C) and Myers Wood Trench M - could not be dated due to significant disturbance of the features prior to excavation. For example, it is considered that the material from the Hagg End Trench 1 hearth feature was either the remains of an *in situ* but highly disturbed hearth or the deposited remains of a furnace and/or heat affected clay, since there was considerable variation in the individual AMD sample declinations and inclinations. The Myers Wood Trench C groups B and C sampled material similarly had substantial variations in individual magnetic directions to the extent that some of the inclinations were negative, leading to the conclusion that this trench contained furnace remains and other heat affected clay material randomly deposited away from their original positions.

3.9 General discussion

The results of the magnetic susceptibility measurements show that there is a wide range of susceptibilities of the slag and other smelting related materials analysed in this research. Figure 3.17 indicates the relationship between the different categories of iron smelting related materials.

As a means of summarising the magnetic effects of the heat affected clays, slags and furnace remains, the predicted responses to a magnetometer/magnetic susceptibility geophysical survey of the principal components of a medieval/post-medieval iron smelting site are shown in Figure 3.30. It should be noted that although the responses of the clay and furnace components are shown as weak to moderate, and strong (respectively), there is an element of overlap in these particular responses. It has been shown elsewhere that the magnetic anomaly or response of a furnace recorded by a magnetometer survey is the combination of the separate anomalies of the furnace lining material (including in-fill material) and the heat affected clay surrounding the furnace remains (Powell *et al*. 2002). In this research, the susceptibility, hence the recorded magnetic anomaly, of the heat affected clay is shown to reduce with distance from the furnace, to the point where the recorded magnetic response is solely from the unaffected natural clay. The clay component shown in Figure 3.30 is, therefore, a blend of the magnetic anomalies or responses of both natural and heat affected clays.

The quantity of smelting slags from Myers Wood with susceptibilities greater than 2000 x 10^{-8} m^3 kg^{-1} was considerable (20% of samples by number or 9% by weight, compared to the Kyloe Cow Beck and Stingamires samples: 3%/1% and 2%/1%, respectively) and certainly would have influenced the interpretation of the magnetometer surveys carried out over the Myers Wood site. The 5m grid magnetometer survey recorded a series of high value anomalies in Trenches C and E (Figure 3.28) which were interpreted as potential furnaces (Vernon 2004). However, on excavation, these anomalies were found to be slag deposits which, when subjected to magnetic susceptibility analysis, had susceptibilities of up to *c.* 14400 x 10^{-8} m^3 kg^{-1} (Trench C) and up to *c.* 12100 x 10^{-8} m^3 kg^{-1} (Trench E) (see Table 3.3). The two Myers Wood trenches and the Stingamires ore roasting area (discussed in section 3.8.2.5) serve as examples of magnetometer survey data interpretations which remain valid until proved to be incorrect on excavation of the anomalies. Potential mistaken interpretations would, therefore, go unrecognised if excavation at a site was not possible; under these circumstances there would be a reliance on geophysical surveys for site descriptions, in addition to any documentary and field evidence.

Operating temperatures in iron smelting furnaces could be predicted to reach in excess of 1000°C and at such temperatures significant enhancement of the magnetic characteristics of the ground surrounding a furnace would be expected, including thermally induced remanence. The extent of the enhancement is dependent initially on there being sufficient iron oxide content in the ground for measurable enhancement to occur, and subsequently on the volume of heat produced in the furnace combustion zone, i.e. the quantity of heat as a function of furnace temperature, length of operation and heat flow into the surrounding clay material. The results of the susceptibility measurements of soils, natural clays and heat affected material from iron smelting sites demonstrate that significant magnetic enhancement has taken place; an indication of the degree of enhancement has been ascertained through a series of heating experiments, including fractional conversion measurements, which are described in Chapter 7.

Whilst the smelting process itself is understood, what is not known is how long the furnaces were operated. There is no evidence to suggest that an iron smelting furnace was run for a specific period. Whether it was operated only once or for a campaign of several months over a number of years dependent on the coppicing cycle for charcoal production is unknown and the use of magnetic geophysical surveys does not provide an answer. In this respect, there is no difference between single-furnace sites, such as Hagg End or Stingamires, and multi-furnace sites like Myers Wood. The single-furnace site may only have a single high value magnetic anomaly identified by the magnetometer survey and interpreted as a furnace anomaly, but excavation evidence demonstrates that the furnace remains may consist of two or three re-linings. This suggests that the furnace could have been operated over a long time scale of several years or just over a single campaign of a few months. The magnetic responses of the individual linings are included in the overall response of the furnace, its in-fill and the surrounding heat affected clay, which is recorded as a single anomaly. Multiple-furnace sites, by their very nature, contain several smelting furnaces, slag deposits and possibly other smelting related activities, often concentrated into a relatively small area. The consequential overlaying of individual magnetic responses, as a result of the physical changes to the site caused by a process of furnace siting and re-siting, and varying slag deposit locations, will complicate a magnetic geophysical survey considerably, and the subsequent interpretation of the data may not be straightforward.

The magnetic surveys and subsequent excavations at Stingamires confirmed the existence of an ore roasting area adjacent to the iron smelting trench (Figure 3.27), although the initial interpretation was of another furnace feature (Figure 3.26). The magnetometer surveys carried out at Kyloe Cow Beck prior to this research (Powell *et al*. 2002) indicate an area of activity north of the eastern smelting furnace (the survey plot is shown in Figure 3.31). It is feasible that this area could be the site of ore roasting, but does not have a pronounced magnetic anomaly compared to that at Stingamires; there is a small cluster of positive data which has a peak of 169nT, compared to the peak of 582nT at Stingamires. Whatever the reason for the difference in peak data values, and a deeper top soil overlay could be one, only excavation of this area will confirm the existence and type of activity believed to be related to the known iron smelting furnace. The ore roaster at Stingamires is the only example discovered so far in Bilsdale.

3.10 Conclusions

For ease of use and maximisation of data, a magnetometer survey employing a fluxgate gradiometer has been shown to be the most appropriate survey method at iron smelting sites. The magnetic susceptibility survey technique should be considered for use at iron smelting sites as a norm to complement magnetometer surveys, but subject to individual site ground surface considerations; the magnetic susceptibility survey results would be used as additional data to enhance the interpretation of a smelting site.

Magnetometer surveys, and magnetic susceptibility surveys where appropriate, have recorded and identified the principal components of the iron smelting sites studied in this research, in particular the spatial extent of the activities related to the smelting process, i.e. ore roasting area, the furnace and the slag deposits. However, there are caveats which need to be considered when interpreting the survey data.

Comparison of the magnetic susceptibilities of iron smelting related materials indicates that a magnetic geophysical survey will be able to identify furnace features and slag deposits, even though these features contain a "mixture" of different materials; however, surveys will not be capable of distinguishing the individual materials.

Measurements of the iron smelting related materials have shown that there is a wide range of magnetic susceptibilities. Some of these materials, especially when they are sparse, such as ore and roasted ore, could easily be undetected during a magnetic geophysical survey. Where a concentration of roasted ore exists, as found on an ore roasting area, the resulting magnetic anomaly could be confused with the anomaly produced by an iron smelting furnace. It has also been shown that it is possible for some smelting slags to have high values of susceptibility, well in excess of the susceptibilities expected of slags from the direct smelting process, which in accumulated deposits would have been recorded as specific high value anomalies not unlike furnace anomalies. There is, therefore, the potential for mis-interpretation of survey data due to similarities in size, shape and strength of magnetic anomalies.

This research has shown that magnetometer surveys undertaken over iron smelting sites also indicate the high value magnetic anomalies which have the potential for archaeomagnetic dating. Many of these anomalies were subsequently dated; the exceptions, those features which could not be dated, were found to be highly disturbed deposits, which could not have been identified as such from the survey data.

Magnetic geophysical surveys do not provide evidence of the length of time an iron smelting site was operated; the physical changes to the site caused by a process of furnace siting and re-siting, and varying slag deposit locations, will complicate a magnetic geophysical survey considerably, and the subsequent interpretation of the data may not be straightforward.

As a consequence of this study into the magnetic characteristics of medieval/post-medieval iron smelting sites, suggestions for further investigations are made in Chapter 12, section 12.2.1.