CHAPTER 4: LEAD SMELTING

4.1 Introduction

The second industry to be considered is lead smelting and in particular the early technology of the smelting process employed in the medieval and post-medieval periods. The purpose of this chapter is to investigate the magnetic signatures of this early technology and to apply the results to improve interpretation of geophysical surveys carried out over lead smelting sites.

4.1.1 A summary of the history of lead smelting

The history of lead smelting is closely allied to that of lead mining and silver production; all are well documented in the literature. Several authors have collectively described lead smelting in Britain, in terms of technology, chronology and geographic location, among them Burt (1984), Blanchard (1981), Crossley (1994: 186-194) and Tylecote (1990 and 1992). Burt (1984: 18) states that lead mining in Britain is usually associated with the Pennines (divided into the four separate areas of the Northern Pennines, the Yorkshire Dales, the Peak District and Cumbria), the south-west of England (principally the Mendips but also including Devon) and Wales (Mid-Wales and Flintshire) (Figure 4.1), although there are other relatively smaller mining areas in Scotland (Tylecote 1990: 54).

The lead ore deposits of the Mendips were probably the first to be exploited, during the Roman occupation for their silver content; the mines were being worked by AD50. The low-silver lead deposits of Flintshire were worked by the late 1st Century, whilst the Derbyshire and Yorkshire deposits were being mined by the first half of the 2nd Century (Fuller 1970; Raistrick and Jennings 1983: 18; Tylecote 1992: 71). Romano-

British lead smelting sites have been discovered in some of the mining districts, for example, on the Mendips at Charterhouse (Todd 1996) and Green Ore (Ashworth 1970), in Flintshire at Pentre Farm and Pentre Ffwrndan (Frere *et al*. 1977; O'Leary *et al*. 1989), and in Mid-Wales at Penguelan (Timberlake 2002). However, few traces of Romano-British lead production have been found in the Pennines: evidence of mining in the Yorkshire Dales is limited to the Hurst Mine, near Marrick in Swaledale, and pieces of lead, ore and slag have been found near Whitley Castle, near Alston (Cumbria) (Raistrick and Jennings 1983: 7, 10).

After the end of the Roman occupation, there appears to be little evidence to date for lead mining and smelting in the early medieval period (Raistrick and Jennings 1983: 19; Tylecote 1990: 70). With the building of the Anglian monasteries, the demand for lead increased. Monastic records show that lead was being mined in Derbyshire at Wirksworth in 835 (Fuller 1970) and near Castleton in the late 9th Century (Ford and Rieuwerts 2000: 19), but not much elsewhere in the region. Ford and Rieuwerts (2000: 18) note that mining continued in the Derbyshire area though on a smaller scale than during the Roman period. During the 12th to 14th Centuries there was a great increase in lead production (a large amount of it being used in the construction of castles and monastic buildings), although the smelting process had changed little. The ore was smelted in boles (Derbyshire), bales (Yorkshire) or bails (Teesdale), all describing the same constructional feature: a simple structure situated on the tops of hills or other exposed places where the prevailing winds would provide the natural draught for the smelting process; bole/bale smelting was essentially a bonfire rather than a furnace technology (McDonnell *et al*. 1992). The bole/bale was the major device used for extracting lead from its ores in the three largest English mining areas from at least the 12th Century until the end of the 16th Century (Kiernan 1989: 40, citing Blanchard

1981). The medieval lead industry was concentrated principally in the Peak District and the Mendips (Tylecote 1990: 71), although there is documentary evidence that the mines at Alston (Cumbria) were worked for lead and silver in the 12th to early 14th Centuries (Tylecote 1992: 89). By the early 15th Century, lead mining and smelting was expanding in the Northern Pennines, in the Derwent valley, upper Teesdale and Weardale (Raistrick and Jennings 1983: 51; Tylecote 1990: 71).

More sophisticated furnaces were developed during the 15th, 16th and 17th Centuries (Blanchard 1981: 77ff; Burt 1984: 207 & 214; Gill 1993: 12; Gill 2001: 19-22; Tylecote 1992: 113), although not all at the same time in all mining districts. These furnaces (the blackwork oven, ore and slag hearths) were bellows-operated, either by foot or water power, and fuelled with peat, wood or charcoal (depending on furnace type) and were used for the initial smelting of the poorer ores and re-smelting of the lead-rich slags from the boles/bales. During the 17th Century and later, reverbatory furnaces (also known as cupolas) were developed which worked the ores and slags at much higher temperatures, using coal as fuel. Burt (1984: 213) also states that at the beginning of the 18th Century, lead smelting was still being carried out in some mining areas in boles or bales whose design had hardly changed since "the middle ages".

Coal-fired reverbatory furnaces were introduced into Flintshire from the early 18th Century, and into Derbyshire and the Pennines from the mid-18th century (Burt 1984: 213), and continued working sporadically until the late 19th and early 20th Centuries.

Additional specific detail of the history of the lead mining districts and the smelting technologies used in them may be found in, *inter alia*: Gough (1967) for the Mendips; Timberlake (2002) for Mid-Wales; Crossley and Kiernan (1992), Ford and Rieuwerts

(2000), Kiernan (1989), and Kiernan and Van de Noort (1992) for the Peak District; Raistrick and Jennings (1983) for the Pennines in general; Gill (1988), Gill (2001), Murphy and Baldwin (2001), and Raistrick (1973) for the Yorkshire Dales; and Beadle (1969), Fairbairn (1996, 2000, 2005), and Pickin (1992) for the Northern Pennines.

4.2 Description of the lead smelting process

The following is a brief description of the lead smelting process in the medieval and post-medieval periods, including a summary of smelting site locations and operating temperatures.

4.2.1 The smelting process

The main components of a medieval/post-medieval lead smelting site, and the inputs and outputs of the process, are shown in the flow diagram of Figure 4.2.

According to Tylecote (1992: 89), the smelting process in the medieval period had changed little since Roman times. Much of the smelting took place in boles or bales situated close to the mines on high ground to take advantage of the natural draught of the prevailing winds. The slags produced had a high lead content, which was recovered, initially, in charcoal-fuelled furnaces known as blackwork ovens: a manually-operated bellows provided the air blast to produce the high temperatures required for the re-smelting (Ford and Rieuwerts 2000: 28). Later re-smelting took place in the water-powered slag hearths, the next technological development in conjunction with ore hearths to smelt lead from the poorer ores.

The principal lead ore is galena (lead sulphide, PbS) and before it could be smelted, the run-of-mine ore was hand-dressed and sorted to remove as much of the gangue material as possible. As smelting technologies improved, the ore was mechanically crushed, sorted and washed at the mine using water-powered machinery, and then transported to the smelt mills which could be at some distance from the mines. Mechanical ore dressing was less effective than hand-dressing and would have resulted in some contamination of the ore by gangue material (Vernon *et al*. 2002).

Gill (1992) describes lead smelting as a two-stage process. The first stage, indeed the only stage until the introduction of blackwork ovens and hearths, took place in boles/bales at temperatures in the range 600 to 800°C. The yield of lead from the bole/bale ranged from 40 to 75% of the ore's metal content (Blanchard 1981: 74; Gill 1992; Murphy 1992) and resulted in lead-rich "grey" slag. The second stage took place in a slag hearth at temperatures between 1000 and 1200°C, producing the familiar lead-poor "black" slag. Based on roast-reduction and/or double decomposition processes, the chemical reactions involved in both stages are complex, often occurring simultaneously but at different positions within the bole/bale, oven or hearth (Blanchard 1992; Hetherington 1978; McDonnell *et al*. 1992; Murphy 1992; Murphy and Baldwin 2001).

The method of smelting lead ore in either a bole or a bale is similar and is described by Blanchard (1992), Crossley (1994: 189), Kiernan and Van de Noort (1992) and Raistrick (1975: 24). High grade dressed ore was mixed with brushwood over layers of more substantial wood or logs laid as a foundation over the hollowed-out hearth. As smelting proceeded at the temperatures noted above, the molten lead was collected in the hollow beneath the bole/bale or led away to a sump adjacent to the hearth. Kiernan (1989: 41, 47) describes smelting using a blackwork oven: lead-rich slags (from the boles) were placed centrally in the hearth and packed around with charcoal. The whole hearth was then sealed with a covering of clay. Manually-powered bellows directed a blast of air into the side of the hearth to produce the high temperatures required to reduce the slag.

4.2.2 Location of lead smelting sites

Boles and bales were usually constructed near to the mines, on remote high ground to catch the prevailing wind and create suitable draught to enable the bole/bale to reach the required smelting temperature. Variation in the draught could cause changes in the bole or bale operating temperature which affected the quantity of the lead produced and the quality of the slags (Burt 1984: 213). Blackwork ovens were located in close proximity to the bole or bale for reasons of convenience (Kiernan 1989: 48), and are often mistaken for them (Blanchard 1981: 78). In the Peak District, there is evidence to show that large boles were established some distance from the mines (Murphy and Baldwin 2001); although a few small boles have been located which could be associated with earlier smelting activity, no systematic large scale search has been carried out to identify further examples (Kiernan and Van de Noort 1992).

In contrast to the boles and bales, the later smelt mills were sited at a convenient focal point for several mines and close to sources of fuel and water power; the distance between the smelt mills and the mines varied according to the type of fuel and furnaces used (Burt 1984: 207ff). Smelt mills were built with one of two types of furnace, depending on mining district and time period: the ore/slag hearth or the reverbatory furnace (cupola). Fuelled with peat/kiln-dried wood (also known as chop wood or white coal) or charcoal, the ore and slag hearths, although often much larger than boles or bales, had a smaller capacity than the cupolas, whilst the latter, using coal as fuel, were capable of a large ore throughput. Where peat or wood was readily available and coal at a distance, ore/slag hearth mills were built in preference to cupolas. This led to the

Yorkshire Dales mining area, being at some distance from the coalfields but having plentiful supplies of peat and wood, generally having small ore/slag hearth smelt mills built near the mines, whilst the Northern Pennines and Derbyshire areas had cupolas constructed on the edge of the coalfields at centralised locations at some distance from the mines (Burt 1984: 207ff).

In geological terms, the location of a lead smelting site could be significant with respect to the potential magnetic enhancement of the underlying ground. Murphy and Baldwin (2001) note that the Swaledale area is a region of "Carboniferous rocks of the Brigantian and Pendleain periods, consisting of cyclical layers of sandstone, shale, chert and limestone". Specifically, bale sites such as at Grinton in Swaledale are on gritstone and limestone units of the Brigantian that lies within the Dinantian division of the Lower Carboniferous (R. Vernon pers. comm.). Within the Peak District, a bole site, such as on Totley Bole Hill west of Sheffield, may lay on top units of the Millstone Grit in the Namurian division of the Middle Carboniferous (R. Vernon pers. comm.). Depending on the precise nature of the geology at a site, there is the potential for magnetic enhancement to occur and thermoremanence to be acquired, assuming that operating temperatures are high enough.

4.2.3 Operating temperatures

Hetherington (1978) showed that under experimental laboratory conditions temperatures around 1000°C were required to obtain lead smelting slags similar to those found on "primitive" smelting sites (these were not defined, but for the purposes of this research are assumed to mean boles, bales and blackwork ovens). Smith (2006a) has similarly demonstrated through experimental procedures that temperatures of 800°C or more would be required to produce the different types of lead slags found at the various bale sites in Swaledale. Tylecote (1990: 128) maintains that the minimum temperature for smelting lead is 800°C, unfortunately without providing further details. Gill (1992) states that lead smelting in a bole or bale was carried out at temperatures in the range 600 to 800°C, which were easily achieved in the natural draught bonfire technology of the bole/bale. The lead-rich slags from the bole/bale smelting and the poorer ores were smelted in blackwork ovens, ore and slag hearths at temperatures between 1000 and 1200°C, which melted the slags/ores to release the lead. Murphy (1992) notes that temperatures in a bole/bale could be as low as 600°C, at which temperature the reduction of lead oxide by carbon monoxide is very rapid. The temperatures required to roast the ore are in the range 500 to 700°C, which could easily be generated near the top of the bole/bale structure, assisted by the strongly exothermic roasting reactions (Murphy and Baldwin 2001). Smelting of the roasted ore takes place at temperatures ranging from 900 to 1100°C as the ore gradually descends into the heart of the fire (Murphy and Baldwin 2001).

4.3 Physical description of a lead smelting site

Since this research is primarily concerned with the lead smelting technologies of the medieval and post-medieval periods, the descriptions will concentrate on the types of site associated with those time periods, namely bales and boles, blackwork ovens, and ore and slag hearths. However, a brief summary of the earlier lead smelting sites is given as an introduction.

At the Romano-British site of Pentre Farm/Pentre Ffwrndan, there is fragmentary evidence of a primitive lead smelting process (Tylecote 1992: 72). It has been speculated that an induced draught shaft furnace of around 1m in height was probably used; much lead was lost to the slag. Tylecote (1990: 57), citing Lane (1973), also briefly describes a Romano-British lead smelting site at Scarcliffe Park, Derbyshire. The remains of the "hearths" consisted of shallow bowls of approximately 1 to 2m in diameter. The remaining slag was dark in colour containing both galena and lead sulphate, but very little metallic lead.

4.3.1 Bole and bale sites

Burt (1984: 213) describes a bole/bale as consisting little more than a pile of stones around a wood-fuelled fire, making use of the prevailing wind. Most bales and boles appear to be ephemeral, since it is virtually impossible to identify recognisable structures. The archaeological evidence for the location of bole/bale smelting is primarily the slag deposits and possible evidence of burning (McDonnell 2001: 497); the position of the bole/bale is rarely discernible compared to the spread of slag and in addition many sites were effectively destroyed because they were often seen by later smelters a source of lead-rich slags (Gill 1998: 14). Murphy and Baldwin (2001) have suggested that bales (and by implication, boles) are temporary structures, concluding that most bale sites have "no associated pit or structure and little slag".

The original construction of a bole/bale is not fully understood and there appears to be some inconsistency in the description of both structures. As Crossley states, the archaeological evidence for the bole is controversial, "for there are discrepancies between hearths which have been accepted as boles and contemporary descriptions" (1994: 188). From the few field observations and documentary evidence, bales could be circular in shape, about 1 to 2m in diameter and surrounded by a low stone wall (Gill 1993: 12; Gill 2001: 19), whilst boles could be rectangular, 3-sided stone structures, with overall dimensions up to 7m x 3m (Kiernan 1989: 41; Kiernan and Van de Noort 1992); both were constructed over a shallow depression. According to Ford and

Rieuwerts (2000: 27), in the Peak District medieval boles were small, about 3ft (0.9m) in diameter and clustered close together; post-medieval boles were much larger, up to 20ft (6m) in diameter, but usually only two or three were located at each site.

Raistrick (1975: 23) recorded a bale in 1919 on Winterings Edge near Gunnerside, Swaledale, which was possibly close to or among the remains of a group of bales; it was a circular dry stone walled construction with an external diameter of 5ft (1.5m) (Figure 4.3). Raistrick gave no date for the bale but Tylecote (1990: 57) considered it to be medieval. As Vernon *et al*. (2002) observe, this state of preservation of a bale feature is probably an exception; unfortunately, the location of this bale site is not now known (Murphy and Baldwin 2001) and further investigations are not possible. An example of the construction of a bole, albeit speculative, is shown in Figure 4.4.

Although there is very little existing evidence, it could be possible for boles/bales to be built within existing structures, rather than as standalone features, as the excavations on Beeley Moor, Derbyshire, have suggested (Radley 1969).

4.3.2 Blackwork ovens

The blackwork oven is reported to be a low circular stone structure, around 1.5m in diameter and 60cm high (Blanchard 1981: 78; Kiernan 1989: 41, 47). However, there is some doubt whether such features are blackwork ovens or boles/bales (Crossley 1994: 189). The bale discovered by Raistrick (1975: 23) (Figure 4.3) may well have been a blackwork oven; both Blanchard (1981: 78) and Kiernan (1989: 47, 291 note 2) make that assumption.

4.3.3 Ore and slag hearths

Ore and slag hearths were the primary lead smelting components of a smelt mill; the general layout is shown in Figure 4.5. The ore hearths were small, bellows-blown structures in which the fuel (peat or chop wood) was mixed with the ore, and were shaped much like a blacksmith's forge, having dimensions in the order of 2ft wide x 1½ft high x 1ft deep (60cm x 45cm x 30cm) (Burt 1984: 214; Gill 1993: 114; Gill 2001: 19, 20). The parts of the hearth were usually made of iron and because they were easily broken up for scrap, no ore hearths survive, but the remains of the arches and flues can often be identified (Gill 2001: 20). The slag hearth was similar to the ore hearth in construction and size, and usually housed in the same building. It was a small enclosed furnace, bellows-blown (the later hearths by water-power) and fuelled with charcoal (or later by coke).

In the Peak District, few smelt mill structures survive, earthworks are on a small-scale and many of the features associated with water power have disappeared due to later changes in land use. In the Yorkshire Dales, there is considerable evidence of the smelt mills which housed ore and slag hearths, but in other lead mining areas such as the Northern Pennines, Cumbria and the Mendips there are fewer examples (Crossley 1994: 191, 192). Typical smelt mills' plans from the Yorkshire Dales are shown in Figures 4.6 and 4.7.

Since the ore (and slag) hearth was similar to a blacksmith's forge, i.e. the hearth was at waist height, it is unlikely that a magnetic signature of the hearth would exist; there was no direct heating of the ground surface as with a bole or bale.

4.4 Lead smelting residues

For the purposes of this research, lead smelting residues are defined as those associated with smelting sites which were built at ground level and as a consequence had the greatest potential for magnetic enhancement of the site. These residues are of the remains of the structure and the slags, and are associated with the boles/bales and blackwork ovens of the medieval/post-medieval periods.

4.4.1 Site structural remains

Features associated with bole/bale smelting are not readily recognisable in the field, due to vegetation cover and apparent lack of stonework on most sites due to a number of factors: the decomposition by weathering of the stone used for building the structure and subsequently burnt during smelting; robbing; demolition and scattering as a consequence of the recovery of metallic lead remaining on the stonework or of the lead-rich slag for re-smelting in the slag hearths (Barker and White 1992). When boles were abandoned their sites were subject to considerable disturbance (Kiernan and Van de Noort 1992). Boles were often broken up for the accumulated lead in the base of the structure, but also to realise the assets of the deceased bole owner for probate purposes. When a bole was finally abandoned, its foundations were removed and its perimeter wall dismantled for access and re-use as walling stone: only the scooped-out hollow and perhaps a scattering of stonework remained. A similar amount of disturbance can be assumed for bale sites and blackwork ovens. Murphy and Baldwin (2001) describe in some detail the remains of over 70 early smelting sites in Swaledale; most of the bale sites had no associated pits or structures and little slag. Some examples of bole and bale smelting site remains are shown in Figures 4.8, 4.9 and 4.10, whilst the remains of what is considered to be a blackwork oven is shown in Figure 4.11.

4.4.2 Slags

The slags from the first stage of smelting, i.e. in boles or bales, were lead-rich and usually of a grey colour (Gill 1992). The second stage of smelting, these "grey" slags were re-smelted in blackwork ovens (or slag hearths), producing slags which consisted primarily of a "black" glassy phase. The small sized, low grade "grey" slags that were considered unsuitable for re-working were left lying around the bole/bale (Kiernan and Van de Noort 1992). Murphy (1992) discusses the examination of slag residues from various smelting sites, which showed that the dominant by-product of both boles and bales, and a "simple ore hearth smelter" was black slag rather than the expected white coated, lead-rich material. In the examination of slags from the Swaledale bale sites, Murphy and Baldwin (2001) and Smith (2006a) identified three types of slag: Type 1, a very dense dark green vitreous slag with a thick yellowish coating; Type 2, a strong black or greenish black slag with a thin white or yellow/white coating, of a fine crystalline appearance and sometimes vitreous; and Type 3, a light coloured non-vitreous slag, of variable hardness and density, and white or grey with pale brown/yellow patches externally and variable colour internally. The types of slag to be found at a bole, bale or blackwork oven site can vary considerably: at some sites most slags will be one type or another whilst at others there may be slags of different types (Smith 2006a).

4.5 Discovery and geophysical survey of lead smelting sites

Lead smelting sites have usually been identified by fieldwalking (Crossley 1994: 189). Examples are the Swaledale survey carried out by Murphy and Baldwin (2001) and by Bevan *et* al. (2004) in the Upper Derwent Valley, Derbyshire. Any remains may be sparse: wall structures would have disintegrated or been removed, and the small amount of scattered slag material is the result of picking-over the lead-rich slags for re-smelting.

There may not be much evidence of heat affected ground and there are only occasional finds of reddened stone (Murphy and Baldwin 2001). The effects of site contamination are also good indicators of smelting activities: patches of ground with little vegetation evident, often supporting only lead-tolerant plants. Geochemical survey techniques have been applied as part of a general assessment of heavy metal soil contamination of industrial sites, including the identification and characterisation of early mining and smelting sites; examples of these techniques are the large-scale surveys undertaken by Wild and Eastwood (1992) in the Peak District and the small-scale survey carried out at Penguelan by Timberlake (2002).

The methodological approach developed for the geophysical survey of iron working sites has been applied to lead smelting sites (Vernon *et al*. 2002). Magnetometer surveys have been carried out prior to this research over bale sites in the Yorkshire Dales, at Grinton and Calver Hill, both in Swaledale (McDonnell *et al* 1992; Hamilton *et al*. 1999). In these examples, the location of the bale could not be positively identified from the survey plots: no relatively high-valued magnetic anomalies which could be associated with a bale structure were detected. As Vernon *et al*. (2002) state, detecting the bale as a circular anomaly (or any other apparent shape) will depend on the original construction of the bale, which may have been of stone or stacked turf. Identifying the apparent rectangular shape of a bole, as suggested by Kiernan and Van de Noort (1992), has similarly difficulties. In contrast, the magnetometer survey undertaken by Vernon at Dacre near Pateley Bridge, Nidderdale, identified a well-constructed bale: a circular anomaly with a linear anomaly (a channel?) leading to a possible casting area (Vernon *et al*. 1999). Low-valued magnetometer readings of up to 22nT were recorded over the circular anomaly, whilst a cluster of higher readings was speculated to be the air admission point into the bale. Magnetometer surveys have also been undertaken at

Grassington Low Mill in Wharfedale. The 18th Century smelt mill had three ore hearths, all supplied with water-powered forced draught. The first survey was carried out over ground outside the mill and only identified a possible water leat. Another survey within the mill did not produce any results which could be reliably interpreted due to the amount of metallic and non-metallic debris scattered across the survey area, except for an anomaly of relatively high-valued positive data (maximum 67nT) which corresponded to the main lead slag dump (Roe *et al*. 1999).

4.6 Dating of lead smelting sites

According to Crossley (1994: 189), dating of bole and bale sites is rarely possible. The use of archaeomagnetic dating (AMD) is implied when he states that a particular difficulty is the relatively low temperatures required for smelting the lead ore; at around 800°C, temperatures are potentially high enough for magnetic enhancement to be achieved but if the smelting operation is not long enough at these temperatures and/or the ground mineralogical conditions are not favourable, then remanence is unlikely to be acquired and AMD is not possible. Providing there is sufficient and suitable charcoal remaining on a lead smelting site, then there is the potential for obtaining a radiocarbon date. The only published report so far of archaeomagnetic dating of bole/bale or blackwork oven sites is that of the bole smelting site at Linch Clough, Derbyshire (Bevan *et al*. 2004). There was sufficient undisturbed burnt material to allow AMD to be undertaken, the result of which was a date range of AD 1430 to 1470 for the last operation of the bole. The author has attempted to carry out AMD of the lead smelting site at Penguelan, near Cwmystwyth (Ceredigion), but the results were inconclusive due to the sample area being more disturbed than anticipated (see section 4.7.3) below). However, charcoal excavated at Penguelan has been radiocarbon dated to the 3rd

Century AD (Timberlake 2002). Barker (1978) and Smith (2006b) report the radiocarbon dating of bale sites in Swaledale to the 15th Century.

4.7 Lead smelting site investigations

Investigations into the process and residues of medieval/post-medieval lead smelting have been carried out along three linked paths: susceptibility measurements of selected samples of lead slag obtained from various sources, geophysical surveys of two known bale sites, and archaeomagnetic dating of a site known to be associated with lead smelting.

The quantity of slag available for sampling was restricted, either as a result of a limited supply being available as a consequence of sites being picked-over for the lead-rich slags for re-working in blackwork ovens or slag hearths (section 4.4), or because a site was a Scheduled Ancient Monument, which prohibited removal of samples. Consequently, the quantity of sample material was not as great as the author had wished, but was considered sufficient to establish the broad characteristics of the material.

During the smelting process, molten lead flowed from the bole/bale or blackwork oven into a clay-lined hollow (Tylecote 1990: 57; Kiernan and Van de Noort 1992). Whether the lead remained long enough in such a position for the clay material to acquire a magnetic enhancement is debatable, and one of the objectives of the geophysical surveys was to attempt identification of such enhancement, both in the hollow and the channel(s) leading to it.

4.7.1 Laboratory measurements

Laboratory measurements of magnetic susceptibility were carried out on two sets of samples: (a) from a number of lead smelting sites, and (b) from the remainder material following preparation for archaeomagnetic dating, as defined in Chapter 2, section 2.6.

4.7.1.1 Site samples

The measurement process followed that described in Chapter 2, section 2.5. A total of 108 samples, from six sources, were prepared for analysis:

(a) Swaledale: a selection of lead slags from various bale sites in Swaledale (17 samples);

(b) Grinton Smeltings (Swaledale): black glassy material with carbonate surface pitting (13 samples);

(c) Spout Gill (Swaledale): black glassy material from two locations (125 and 132) at the lower site, equating to SPG1 and SPG2 in the bale site listing of Murphy and Baldwin (2001) (17 samples);

(d) Penguelan, Cwmystwyth: heat affected stone from bole structures (12 samples); baked clay/stone with attached slag (5 samples); glassy slag material from three boles (8 samples); unidentified material (undressed ore?) (4 samples);

(e) Botchergate, Carlisle: black glassy slag material from a Romano-British site (14 samples);

(f) Pentre Farm and Pentre Bridge, Flint: grey and black slag material from two Romano-British sites (18 samples).

Samples from sources (a) to (d) are slags and other material from medieval/post-medieval bole/bale sites, whilst those from sources (e) and (f) are slags from three Romano-British sites included for comparison purposes only, in an attempt to identify any significant differences in magnetic susceptibility of slags from different lead smelting technologies.

The results of the susceptibility measurements are shown in Tables 4.1 for sources (a) to (d) and Table 4.2 for sources (e) and (f), both tables derived from the calculations in the attached Appendices 33 to 38. Not all the magnetic quadrature susceptibility measurements for the Swaledale samples (Table 4.1) could be made due to the readings of some of the samples proving to be very low and within the noise levels of the PIM instrument, and as a consequence were deemed to be unreliable. Two of the Penguelan samples (Table 4.1: Stone - C and Stone - E) were both physically small, but had relatively high magnetic susceptibility and caused an overload of the PIM instrument reading; it was not possible to sub-divide the samples, in order to bring the PIM readings into range, without effectively destroying them. In general, the measured susceptibility values of the slag samples, shown in Figure 4.12, were low in comparison with slags selected from the Kyloe Cow Beck and Myers Wood iron smelting sites (Chapter 3, section 3.8.1.1). However, the susceptibilities of the high valued samples from Spout Gill location 132 and of the Penguelan stone samples are considerably higher than those of both the lead and iron smelting slag samples.

Excluding the 53SGL samples, the mass specific susceptibility of the Swaledale samples ranged from 1 to 10 x 10^{-8} m^3 kg^{-1} with a mean of 5 x 10^{-8} m^3 kg^{-1}. The susceptibility of sample 53SGL1 was 28 x 10^{-8} m^3 kg^{-1} and of sample 53SGL2 was 6137 x 10^{-8} m^3 kg^{-1}. The latter was possibly caused by an iron-based inclusion. The susceptibility range of the Grinton samples was 4 to 269 x 10^{-8} m^3 kg^{-1}; excluding samples GS-B, GS-K and GS-M, the mean dropped from 50 to 8 x 10^{-8} m^3 kg^{-1}. These three samples had high susceptibility values (269, 72 and 234 x 10^{-8} m^3 kg^{-1} respectively) possibly caused by iron-based inclusions or baked clay/stone attached to the slag. The susceptibility of the Spout Gill location 125 samples ranged from 13 to 852 x 10^{-8} m^3 kg^{-1} with a mean of 191 x 10^{-8} m^3 kg^{-1}, which reduced to 32 x 10^{-8} m^3 kg^{-1} when samples 125-A and 125-F were excluded (the high susceptibilities of these may have similar causations as the other excluded samples above). The selection of the above high susceptibility samples was made on an arbitrary basis, i.e. the author took the subjective view that they were "outliers" within their respective sample groups; removal of them was a test to observe the amount of change in the mean values of susceptibility. Spout Gill location 132 samples were divided into two susceptibility groups: a low valued group which was similar in range and mean to location 125, and a high valued group whose susceptibility range was 1816 to 9204 x 10^{-8} m^3 kg^{-1} with a mean of 6031 x 10^{-8} m^3 kg^{-1} and possibly caused by iron-based inclusions or burnt stone attached to the slag. The results of the Penguelan sample measurements were as expected: the heat affected stone and baked clay/stone with slag attached had susceptibility values in the range 133 to 2000 x 10^{-8} m^3 kg^{-1} with means of 1086 and 344 x 10^{-8} m^3 kg^{-1} (respectively); the lightweight slag ranged from 102 to 652 x 10^{-8} m^3 kg^{-1} (mean = 377 x 10^{-8} m^3 kg^{-1}); and the heavier slag and unidentified (ore) material ranged from <1 to 6 x 10^{-8} m^3 kg^{-1} (mean = 2 x 10^{-8} m^3 kg^{-1}).

The slag samples from the three Romano-British sites had susceptibilities ranging from <1 to 227 x 10^{-8} m^3 kg^{-1} and a combined mean of 25 x 10^{-8} m^3 kg^{-1}. Excluding the "outlier" of Botchergate sample 160, the range became <1 to 73 x 10^{-8} m^3 kg^{-1} and the mean reduced to 19 x 10^{-8} m^3 kg^{-1}. These susceptibility values are higher than the medieval/post-medieval equivalents and are likely to be a function of the iron content of the ore rather than differences in the smelting processes.

All the lead slag samples had mean values of mass quadrature specific susceptibility of 1 x 10^{-8} m^3 kg^{-1} or less, an indication of a small mineral grain size. The remaining heat affected stone and other slag samples had mean values in the range 15 to 58 x 10^{-8} m^3 kg^{-1}. The values of magnetic viscosity for the lead slag samples, including "SG 125" and "SG 132 low", ranged from 1.6 to 14.0%, but, since the mass quadrature specific susceptibilities were low and within the noise levels of the PIM instrument, must be regarded as unreliable. The magnetic viscosity of the remaining samples ranged from 0.3 to 6.3%.

4.7.1.2 Archaeomagnetic dating sample remainder material

Archaeomagnetic dating of hearth PSS4 on the lead smelting site at Penguelan, near Cwmystwyth (Ceredigion), was undertaken as part of this research programme; the report is attached as Appendix 53 and is summarised below in section 4.7.3. A total of 14 heat affected samples were obtained from the clay structure at the base of the hearth, using the standard disc method (Chapter 2, section 2.6). Six of these samples had sufficient material left over from trimming (the remainder material) to allow susceptibility measurements to be made; the results are shown in Table 4.3 (derived from the calculations in the attached Appendix 39). The mass specific susceptibility of these six samples ranged from 396 to 799 x 10^{-8} m^3 kg^{-1} with a mean of 577 x 10^{-8} m^3 kg^{-1}. All 14 samples had weak magnetic intensities when measured by a spinner magnetometer as part of the archaeomagnetic dating process (Chapter 2, section 2.6.1, and section 4.7.3 below).

4.7.1.3 Discussion

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

Comparison of magnetic susceptibilities of the different types of samples from the six sources listed in section 4.7.1, recorded in Tables 4.1 and 4.2, and illustrated in Figures 4.13 and 4.14, indicates that there are five sample groups:

(1) Swaledale slag, Grinton Smeltings slag, Penguelan "heavy" slag and ore material, excluding the "outliers" noted above in section 4.7.1.1: very low values of mean magnetic susceptibility ranging from 2 to 8 x 10^{-8} m^3 kg^{-1};

(2) Pentre Bridge, Pentre Farm and Botchergate slags: mean magnetic susceptibilities of 13, 21 and 36 x 10^{-8} m^3 kg^{-1} (respectively);

(3) Spout Gill "125" and "132 low" slags, excluding the "outliers" noted above in section 4.7.1.1: mean magnetic susceptibilities of 32 and 42 x 10^{-8} m^3 kg^{-1} (respectively);

(4) Penguelan "light" slag and baked clay/stone with attached slag: mean magnetic susceptibilities around 360 x 10^{-8} m^3 kg^{-1};

(5) Penguelan stone and Spout Gill "132 high": very high mean magnetic susceptibilities of 1086 and 6031 x 10^{-8} m^3 kg^{-1}(respectively).

Groups 1 to 3 comprise all the samples of lead slag and ore material, irrespective of the period in which the smelting took place. Groups 4 and 5 encompass the high susceptibility samples: slag material separate from or attached to baked clay/stone, and heat affected stone.

The Romano-British slag samples (group 2) have susceptibility values which appear to be at variance with the medieval/post-medieval samples of groups 1 and 2; this suggests that there could be differences between the Romano-British and medieval/post-medieval lead smelting technologies, but the variations are more likely to originate from the different amounts of iron derivatives contained in the lead ore. However, the differences are not significant when comparison is made with the susceptibilities of sample material from other industrial sites.

The susceptibilities of the archaeomagnetic dating sample remainder material from the Penguelan PSS4 lead smelting hearth were compared with the mean susceptibilities of heat affected clays associated with the Myers Wood (MW) iron smelting site near Huddersfield: MW heat affected clay (1) = 615×10^{-8} m^3 kg^{-1}, MW heat affected clay (2) = 708×10^{-8} m^3 kg^{-1}, and PSS4 heat affected clay = 577×10^{-8} m^3 kg^{-1}. The similarities in these susceptibilities suggest that the PSS4 hearth material was heat affected, but not sufficiently to produce a strong magnetic intensity in each of the remainder material samples.

The reasons for high susceptibility values in slag samples similar in morphology to Swaledale 53SGL2 ($\chi = 6137 \times 10^{-8}$ m^3 kg^{-1}) are not fully understood, but these high values may be due to iron-based inclusions existing within the samples. These inclusions, of course, may not be associated with the lead smelting process but are magnetically strong enough to cause a spike or singularity in the geophysical (magnetometry) survey data and could be misleading in the interpretation of the data.

The susceptibilities of the lead slags, excluding the "outliers" in section 4.7.1.1, have been compared with those of soil and natural clay samples from the Dalby experimental charcoal kiln (Chapter 6), Greencliffe Hag Wood charcoal platform D (Chapter 6) and the iron smelting sites of Myers Wood (Huddersfield), Ewecote, Hagg End, Kyloe Cow Beck and Stingamires (Bilsdale, N. Yorkshire) (all Chapter 3). They have also been compared with the susceptibilities of the other lead smelting residues from Spout Gill location 132 and Penguelan, as well as the heat affected (baked) clay samples from the same Bilsdale iron smelting sites listed above. Allowing for differences in geology and other factors associated with the industrial activities at the various sites mentioned above, it can be seen from Figure 4.13 that the lead slag susceptibilities cover a wide low-valued range, i.e. from 1 to 70 x 10^{-8} m^3 kg^{-1}, which is similar to those of the soils and natural clays. In addition, the Penguelan ore material susceptibility range of 1 to 3 x 10^{-8} m^3 kg^{-1} is considerably less than that of the soils and natural clays. In comparison with the iron smelting sites' heat affected clays and the other heat affected lead smelting residues, such as the Penguelan stone and Spout Gill 132 high-valued samples, all the slags have significantly lower susceptibility values (Figure 4.14). With such low susceptibilities, the discovery of lead slags, as well as ore material, would be difficult using geophysical survey methods alone; the magnetic anomalies created by the slag may not be distinguishable from the background anomalies derived from the soil, natural clay material and geology of the site, and would certainly be swamped by the heat affected stone anomalies, assuming that there was sufficient heat affected stone remaining on site. As a means of summarising the above, Figure 4.15 indicates the predicted responses to magnetic geophysical survey of the principal components of a lead smelting bole/bale site.

The amount of lead slag at a site, hence the quantity of samples obtained, is dictated by how much of the lead-rich slag was recycled. It would appear that not every piece of lead-rich slag was taken; what was left behind may not necessarily be representative of the slag produced on the site. Additionally, the amount of heat affected stone samples depends on how much robbing out or dispersal of the bole/bale structure occurred after the site fell out of use. If there was sufficient heat affected stone remaining of the bole/bale structure not robbed or dispersed, then the spread of stone on the site might be over-represented compared to the remaining slag. At the two lead smelting sites surveyed for this research, this was not the case as no heat affected stone was observed, but this does not necessarily mean that other sites would be similar.

The comparison of lead slag susceptibilities suggests that a magnetic geophysical survey might encounter difficulties in identifying slag deposits from any lead smelting technology which was ground based, when taking into account the levels of magnetic susceptibility of a site's soil and its geological characteristics.

4.7.2 Geophysical surveys

The patches of rough vegetation-free ground and lack of definitive structure within them, noted above in section 4.4, does not fit well with the "circular" or "rectangular" descriptions given above for bole or bale sites in section 4.3.1. Geophysical surveys were considered the most appropriate method to discover if any features remained of the size and shape of the bole/bale structure, or of the smelting process.

Geophysical surveys using magnetometer (fluxgate gradiometer) and earth resistance methods were undertaken at two medieval/post-medieval lead smelting sites, Grinton Smeltings in Swaledale, and Totley Bole Hill near Sheffield, and are reported on in the following sections. Magnetic susceptibility measurements using a Bartington MS2D field coil were considered but not carried out as the ground surface over the survey areas at both sites varied between open soil and stone, through rough grass to heather cover, none of which were conducive to giving good and consistent field coil contact and reliable readings.

4.7.2.1 Grinton Smeltings bale site

The Grinton Smeltings bale site is one of a large number of lead smelting sites in Swaledale and Arkengarthdale which have been identified by fieldwalking and reported on by many researchers including Murphy and Baldwin (2001). Up until the author's survey, very few geophysical surveys have been undertaken over smelting sites in Swaledale; two magnetometer surveys which have been published are of the sites at Calver Hill 1 (Hamilton *et al*. 2002) and Grinton Smeltings (McDonnell *et al*. 1992). The geophysical survey carried out by the author was also at Grinton Smeltings but over an area approximately 100m to the north of the previous survey.

4.7.2.1.1 Grinton Smeltings site location

The Grinton Smeltings site is located near Grinton Lodge approximately 0.7km due south of Grinton village in Swaledale, at NGR SE 046 977 (Figure 4.16), and situated above a steep downslope overlooking the junction of the Leyburn and Reeth roads. The area is characterised by a thin grass and heather-covered top soil with some stones visible throughout, and a large (*c*. 10m x 5m) bare patch of stone fragments and lead slag at the presumed position of the bale (Figures 4.17 and 4.18).

4.7.2.1.2 Survey dates, sequence and techniques

The survey was carried out on 29th July 2005, in damp, overcast weather. Two survey techniques were utilised: magnetometry, using a Geoscan FM256 fluxgate gradiometer, and earth resistance, using a Geoscan RM15 instrument (twin probe array, 0.5m mobile electrode spacing). The survey base line was established with reference to a large stone, identified on Figure 4.19, extending eastwards for 40m towards a mobile phone mast. Twelve 10m x 10m grids were laid out over the site and magnetometer readings taken over this area at a resolution of 0.5m (0.5m intervals at 0.5m traverses), with the instrument sensitivity set to 0.1nT. Earth resistance readings were taken at the same resolution over the four grids which covered the bare patch of ground noted above. Six 5m x 5m grids were laid out over the bare patch and surveyed with the magnetometer at 0.25m resolution (0.25m intervals and 0.25m traverses) and instrument sensitivity of 0.1nT. Figure 4.19 shows the 10m and 5m grids superimposed on the site plan.

4.7.2.1.3 Geophysical data

The magnetometer survey plots of the raw data clipped to various ranges (Figures 4.20 and 4.21) highlight the generally low values of recorded data. As the clipping level is reduced, distinct features can be observed and these are discussed below. Several singularities were noted, either as relatively high valued magnetic anomalies or "dummy" data values where the readings were over-range; all were assumed to be isolated pieces of ferrous material. The mean value of the 10m grid magnetometer raw data was 0.7nT, the standard deviation 6.8nT and the data range -82 to 148nT. The majority of the readings in grids 9, 10 and 12 (Figure 4.19) were associated with dumps of modern material; discounting these and the data recorded over the bare patch, the mean reduced to 0.6nT and the standard deviation to 1.3nT, whilst the range became -11 to 23nT. The 5m grid magnetometer raw data gave a mean of 0.4nT, a standard deviation of 9.9nT and a range of -185 to 155nT. Removing the data from the top of grid 14 (ferrous material) and the bottom of grid 17 (the edge of the modern dump), the mean altered to 0.5nT, the standard deviation reduced to 4.9nT and the range changed to -17 to 28nT. Figure 4.22 shows the raw and clipped data from the earth resistance survey. The mean value of the raw data was 183 ohms, the standard deviation 47 ohms and the data range 79 to 827 ohms. Many of the high values were associated with the modern dump material in grid 10, but the highest reading of 827 ohms was within the patch of bare ground and was probably caused by poor mobile probe contact. Some weak anomalies are identifiable. The magnetometer and earth resistance survey data are shown superimposed on the site plan in Figures 4.23, 4.24 and 4.25 (the approximate location of the bare patch of ground has been omitted for clarity).

4.7.2.2 Totley Bole Hill bole site

Totley Bole Hill is part of the Blacka Moor Nature Reserve, which is administered by the Sheffield Wildlife Trust, and has been designated a scheduled ancient monument by English Heritage (monument number 24985) due to the numerous medieval and post-medieval lead smelting activities known to have taken place. Much research has been undertaken into the history of the early lead mining and smelting industries, an example of which is Kiernan (1989). The Totley Bole Hill area has been surveyed previously by fieldwalking and several lead smelting sites noted, in particular a "bole" feature towards the southern end of the hill which has been reported on by Kiernan and van de Noort (1992). Ed Dennison Archaeological Services Ltd. undertook a topographical survey in 2003 which identified in greater detail the bole and some other sites believed to be blackwork ovens (Dennison & Richardson 2003); as far as is known, the author's geophysical surveys are the first to have been undertaken on Totley Bole Hill. The geophysical survey report, which is attached as Appendix 40, has been sent to English Heritage and South Yorkshire H.E.R. (as a requirement of the survey licence), and to the Sheffield Wildlife Trust.

4.7.2.2.1 Totley Bole Hill site location

Totley Bole Hill is located approximately 10km (6¼ miles) south-west of Sheffield city centre, at NGR SK 290 798 (Figure 4.26). The overall plan of the southern end of Totley Bole Hill where the survey was carried out is shown in Figure 4.27 and indicates the general topographic features, the lead smelting sites and the survey locations; the geophysical survey carried out by the author used the site numbers designated in the Dennison and Richardson (2003) survey. The main complex of sites are at the southern end of the Bole Hill (Sites 10 to 15), whilst a second area (Site 22) is approximately 110m north of Site 10. Figures 4.9 and 4.28 are photographs of Site 10 and Site 22 (respectively).

4.7.2.2.2 Survey dates, sequence and techniques

The geophysical survey was undertaken on several dates during the summer of 2005: 2nd June, 28th July, 1st August and 11th August. The weather was extremely varied from high winds and rain (2/6 & 28/7), hill fog and rain (1/8) to dry and sunny (11/8). Two survey techniques were employed: magnetometer, using a Geoscan FM256 fluxgate gradiometer, and earth resistance, using a Geoscan RM15 instrument (twin probe array, 0.5m mobile electrode spacing).

The survey was carried out in two parts, one over the main complex (Sites 10 to 15) and the other over Site 22. The survey base line was initially established within the main complex area but was extended northwards for 110m to link together the Site 22 and main complex survey grids. The error associated with the setting-up of the grids was no more than 10cm in both north-south and east-west directions.

On 2nd June 2005, six 5m x 5m grids were laid out specifically over Site 10, the bole reported by Kiernan and van de Noort (1992), in order to identify better any anomalies associated with the bole. Both magnetometer and earth resistance readings were taken over these six grids at 0.25m resolution (0.25m intervals and 0.25m traverses). In the larger area of the main complex (Sites 10 to 15), a total of sixteen 10m x 10m grids were laid out on different days, as a consequence of the poor weather conditions: six on 28th June 2005, six on 1st August 2005 and four on 11th August 2005. The data recorded on each of these days were merged to form the composite survey data. Magnetometer readings were taken over this area at a resolution of 0.5m (0.5m intervals at 0.5m traverses) with the instrument sensitivity set to 0.1nT. Figure 4.29 shows the layouts of and relationship between the 5m and 10m grids.

At Site 22 on 11th August 2005, six 10m x 10m grids were laid out as shown in Figure 4.30, and magnetometer readings also taken at 0.5m resolution and instrument sensitivity of 0.1nT. In addition, a separate set of magnetometer readings were taken in Site 22 grid 2 at 0.5m resolution but at an instrument sensitivity of 1nT, due to a very high positive anomaly being identified in this grid causing the instrument to over-range on the 0.1nT sensitivity setting.

4.7.2.2.3 Main complex (Sites 10 to 15) geophysical data

Figure 4.31 shows the raw 10m grid magnetometer data clipped to various ranges. As the clipping level reduces various archaeological features emerge. Distinct areas of activity are identifiable as well as other weak anomalies; these are discussed in detail below. The mean value of the raw data from these 16 grids is 0.2nT; the standard deviation is 10.3nT. Although the data are generally of low positive and negative values, maximum values of 205nT and -119nT were recorded. These two readings are not directly related as they are about 23m apart, and consequently could be generated by *inter alia* individual stray iron-based objects lying below ground surface. Figure 4.32 shows the 10m grid magnetometer survey data superimposed on the detailed plan of the main complex.

4.7.2.2.4 Site 10 geophysical data

Figure 4.33 shows the 5m grid magnetometer and earth resistance survey raw data clipped to various ranges. The mean value of the raw magnetometer data is 0.6nT; the standard deviation is 23.8nT. The maximum values recorded were 252nT and -126nT. A distinct area of activity is noted.

The mean value of the raw earth resistance data is 160 ohms and the standard deviation is 52.8 ohms. The maximum and minimum values recorded were 616 and 96 ohms. Due to its isolated position, the maximum value is considered to have been caused by poor contact. For the clipped resistance ranges, a data area was selected specifically over the presumed location of the bole (grids A, B and C in Figure 4.29), thereby making the interpretation of the plots easier by removing the influence of the data derived from the adjacent path. Two very weak anomalies are identifiable.

4.7.2.2.5 Site 22 geophysical data

Figure 4.34 shows the raw magnetometer data clipped to various ranges. Distinct areas of activity are identifiable; these will be discussed below. The mean value of the raw data from these 6 grids is -0.9nT and the standard deviation is 22.8nT; the maximum values recorded were 194nT and -150nT. Excluding the data from grids 1 and 2, the raw data values become -1.6nT (mean), 7.2nT (standard deviation) and 55nT/-58nT (maxima). The raw data for the single survey over grid 2 produced a mean value of

33nT, a standard deviation of 245nT and maxima of 1757nT and -158nT. The plot of the single set of data from grid 2 is dominated by the very large positive anomaly (greater than 2000nT) which overwhelms any weaker anomalies as the clipping level increases. A similar effect can be seen in grid 1 caused by another relatively high positive anomaly. The white area in the north-west corner of grid 2 (Figure 4.34) is caused by over-range values in the data recording. Figure 4.35 shows the 10m grid magnetometer survey data superimposed on the detailed plan of Site 22.

4.7.2.3 Discussion

4.7.2.3.1 Grinton Smeltings bale site

The magnetometer data recorded in grids 17 and 18 of the 5m survey and grids 1, 2, 3, 4, 7, 8 and 11 of the 10m survey (Figure 4.19) indicate how "quiet" the site is magnetically and consequently provide a low background level against which any enhancement due to the smelting activities can potentially be measured. The bale sites at Grinton Smeltings are on privately owned, public access land so it is possible for ferrous material to have accumulated, which would have had a detrimental effect on recording the archaeological magnetic data of a site. Many bale smelting sites in Swaledale and other upland areas of the Pennines are on open moorland, often access-restricted, and are used for grouse shooting and other recreational activities; similar ferrous material intrusions are to be expected.

Several anomalies were identified from the magnetometer and earth resistance survey data and are shown in Figure 4.36. Anomalies (a) and (b), from the magnetometer surveys, are associated with the bare patch of ground and the modern dump material (respectively). Anomaly (a) lies over the north-western part of the bare ground towards the downslope and corresponds to the scatter of debris from lead smelting. This might suggest that the bale lies on the south-eastern part of the patch within grids 15, 17 and 18 (Figure 4.19). There is no indication of the exact location of the bale on this bare ground from either the magnetometer or the earth resistance surveys. Several dummy data values, 21 in total, were required in the magnetometer surveys, being divided almost equally between both the 10m and the 5m surveys; all were single point anomalies caused by ferrous material. The scatter and location of these singularities suggest that they are modern objects either from the dumps that have worked their way northwards and downhill towards the bale site or trodden in by walkers. Anomalies (b) are associated with the modern dumps and indicate the extent to which the material is intruding onto the bale site.

The remaining anomalies (c) to (e) are all identified from the earth resistance survey data. Of the five anomalies (c), the two larger ones in grids 14 and 15 (Figure 4.19) might indicate hard-standing or a similar feature on which a bale was constructed, but as there was no corresponding high valued anomaly observed in either of the magnetometer surveys, it is considered that these anomalies are the responses to geological features. The remaining earth resistance survey anomalies (c), (d) and (e) are also considered to be geological responses.

There were no indications of remanence recorded anywhere within the areas surveyed by magnetometry which could be solely attributable to thermoremanence; if the heating effect of lead smelting had been sufficient for the acquisition of TRM, then magnetometer readings of at least 200nT and possibly up to 900nT would have been recorded, and this was not the case.

4.7.2.3.2 Totley Bole Hill bole site

Several identifiable anomalies from the analysis of the main complex (Sites 10 to 15) magnetometer and earth resistance survey data are shown in Figure 4.37; these anomalies are marked by lower-case letters and where appropriate referenced by grid locations in Figure 4.29. Similarly, the anomalies identified from the Site 22 magnetometer survey data are shown in Figure 4.38, marked by upper-case letters and where appropriate referenced by grid locations in Figure 4.30.

The magnetometer surveys revealed considerable activity, larger than that suggested by the Dennison and Richardson (2003) topographical survey, both over the main complex (Sites 10 to 15) and Site 22. At the main complex, two sub-circular areas of concentrated activity have been identified, anomalies (a) and (b); both anomalies are apparent over a wide range of clipped data from ±100nT to ±10nT (Figure 4.31). In addition, a large area of (weaker) activity, anomaly (d), lies below anomalies (a) and (b) on the western downslope of Totley Bole Hill. Anomaly (a) in Figure 4.37 does not coincide with the bole identified by Kiernan and van de Noort (1992) (Figure 4.4), or surveyed by Dennison and Richardson (2003), i.e. Site 10/1 in grid 8 of Figure 4.29; instead, the anomaly corresponds more with Site 10/2 in grid 11. There is no evidence from the magnetometer data of any anomalies which coincide with the Kiernan and van de Noort (1992) lead channels (Figure 4.4) and labelled 10/3 and 10/4 in Figure 4.29. This does not mean that these channels do not exist; there may not be a sufficiently high magnetic signal from them which stands out against the surrounding background data. Anomaly (b) is similar in shape and size to (a), but is not visible on the ground, being buried under grass-covered topsoil. Anomaly (c), a weak rectangular anomaly lying between (a) and (b) but which is less distinct than either over the same ranges of clipped data (Figure 4.31), could be associated with a structure of some kind but there is no obvious supporting topographical evidence. There is a sufficient quantity of lead slag remaining in the bare patches of ground on the flat area of the main complex site to conclude that there was a significant amount of lead smelting taking place here; the anomalous areas (a) and (b) have a high probability of being directly related to the smelting process whilst anomaly (d) could be an extensive slag dump.

The remaining anomalies from the main complex magnetometer survey (Figure 4.37) are discussed as follows. Anomaly (g) is an area of weak activity, coinciding with Site 13 and extending south-westwards across the path (Figure 4.37). Site 13, described as mounds by Dennison and Richardson (2003), and its immediate surroundings are covered by bare soil and stones. To the south of Site 15, described by Dennison and Richardson (2003) as a possible blackwork oven or slag hearth, is anomaly (h), an area of weak activity which coincides with the spur of land in grid 15 of Figure 4.37; there is no visible presence here of any slag or burnt material. Anomaly (i) is a weak circular anomaly coinciding with the area of charcoal and bare soil shown in grid 12 of Figure 4.37. Anomalies (e), (f) and (j) are sub-rectangular or sub-circular areas with maximum positive values ranging from 22 to 132 nT; it is possible that they are all small groups of burnt stones buried under either rough grass cover or a thin layer of grass-covered top soil. Anomalies (k) are weak linear anomalies which do not correspond to site topography and could be the response to geological features.

The anomalies above have been determined from the main complex magnetometer surveys. The earth resistance survey over Site 10 resulted in only two weak anomalies (l) being identified, shown dashed in grids 7 and 8 (Figure 4.37). The smaller, oval anomaly (grid 7) overlaps the other larger, circular anomaly (grid 8), and also coincides with the magnetometer anomaly (a). It is possible that the smaller anomaly is part of a structure but this is unlikely to be proved without intrusive investigation. It is also feasible, however, that both anomalies are the responses to geological features.

From the magnetometer survey of Totley Bole Hill Site 22, two areas of activity, (C) and (D), have been identified, spread over grids 1 and 3 in Figure 4.38. Anomaly (C) corresponds with the topographic features west of the path whilst anomaly (D) coincides with the areas of slag and bare soil identified by Dennison and Richardson (2003). Due to the large amount of lead slag material which is visible close to both anomalies, either in the patches of bare soil or along the path, it is possible that these two areas are associated with slag heaps. It is also feasible that anomaly (D) could be the site of another lead smelting bole, although there is no supporting topographical evidence such as a sizeable quantity of stones and patches of bare soil as seen at Site 10. Anomaly (E) is an area of significant activity spread over the survey area as shown in Figure 4.38; the anomaly is not visibly obvious as it is buried under a combination of heather, rough grass or a thin layer of grass-covered top soil. The extent of anomaly (E), running in a south-east/north-west direction along the downslope contours to the north of anomaly (D) and the similarity of its magnetometer data values to the main complex anomaly (d), suggests that this area could also be a slag dump. Anomaly (A) is a very large positive anomaly, shown in grid 2 of Figure 4.30, and anomaly (B) is a sub-rectangular area of relatively high positive data values, which could be either connected with (A) or possibly geological in nature. Further investigation is required to determine the cause of anomalies (A) and (B), and it is possible that either or both are masking additional low level activity similar to anomalies (d) and (E) above. Seven weak linear anomalies (F) can be observed which do not correspond to site topography and could be the response to geological features.

Although the results showed that a speculative interpretation was possible, the earth resistance survey over Totley Bole Hill Site 10 was not as successful as originally anticipated and appears to have been affected by two factors: (a) site geology – soil erosion along the path (Figure 4.29) has revealed many pieces of naturally occurring stones just below ground surface which suggests that there is only a thin layer of top soil on this part of Totley Bole Hill, and (b) ground water content – it is extremely likely that the data were influenced by the heavy rainfall that occurred immediately before and during the survey. These factors do not suggest that earth resistance surveys should not be attempted at other similar lead smelting locations.

Similar to the Grinton Smeltings findings (section 4.7.2.3.1), there were no indications of remanence recorded anywhere within the areas of the main complex and Site 22 surveyed by magnetometry which could be solely attributable to thermoremanence.

4.7.3 Archaeomagnetic dating of a lead smelting site

In March 2003, at the invitation of Dr. Simon Timberlake of the Early Mines Research Group, the author carried out archaeomagnetic dating of the lead smelting hearth PSS4, one of four bole structures which had been excavated at Penguelan, near Cwmystwyth, Ceredigion (NGR SN808748). The site, is situated at the base of Copa Hill and lies in an area of prehistoric, medieval and post-medieval mining and smelting activity. Circumstantial evidence suggested that the medieval mining and smelting may have been carried out under the auspices of the Cistercian abbey of Strata Florida (S. Timberlake pers. comm.). Site geology consists of interbedded grey shales and sandstones, with substantial amounts of quartz and feldspar. The remains of PSS4 were no more than 10cm below ground level, consisting of a reddened heat affected clay/gravel mix hearth surface surrounded by rocks to form the furnace structure; the rocks appeared to be naturally positioned rather than manually placed. Following excavation, approximately one quarter of the hearth remained, with exposed dimensions of 100cm long by 60cm wide. The excavations revealed that the furnace had had three base levels, suggesting two occasions of repair or refurbishment; the top (latest) level was to be dated.

4.7.3.1 Sampling and measurement procedures

A total of 14 oriented samples were taken from the heat affected base material of the hearth, 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 four pilot samples, using the method described in Chapter 2, section 2.6.2. Six 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 4.7.1.2).

4.7.3.2 Measurement results

The intensity of NRM was variable, ranging from 0.6 to 30.5mA m^{-1}, with a mean of 5.9mA^{-1} and a standard deviation of 7.7mA^{-1}, possibly reflecting the variation in the physical size of the samples, inhomogeneous firing or varying concentrations of remanence-carrying minerals. All the samples had magnetic intensities which were measurable, but ten samples had magnetic intensities which were low and may have been compromised by the noise levels of the spinner magnetometer. Each of the four pilot samples was subjected to the full range of a.f. demagnetisation fields, and both intensity spectra and Zijderveld plots constructed (see Figures 4.39 and 4.40 for examples). The intensity spectra of the pilot samples were very similar in shape with median destructive fields of 8, 10, 15 and 18mT; the mean value of 13mT suggests a material which has a relatively “soft” magnetism (C.M. Batt pers. comm.). The Zijderveld plots demonstrated that the hearth material had a small amount of viscous remanence in addition to a component predominantly associated with the geomagnetic field at the time of the last hearth cooling. The stability index (SI), as defined by Tarling and Symons (1967) (see Chapter 2, section 2.6), was calculated for each of the pilot samples; the results - 1.2, 2.8, 3.3 and 5.2 – suggested that the sample material could be considered as generally having a stable magnetisation. The magnetic direction scatter did not alter significantly and remained wide after demagnetisation of the samples in peak applied fields of 10, 15 and 20 mT; Figure 4.41 shows the stereo plots for the NRM and 10mT directional data. Mean values of declination and inclination, and the error at the 95% confidence level (α_{95}) were calculated for the three sets of demagnetisation data; the 10mT data set was chosen for the final calculations as this gave the optimum value of α_{95}.

4.7.3.3 Dating of the measured magnetic direction

The mean declination and inclination after demagnetisation in a field of 10 mT were corrected to Meriden, the reference locality for the British calibration curve, using the standard method (Noel and Batt 1990). As the α_{95} for the demagnetisation results had not improved sufficiently compared to the original NRM α_{95}, remaining excessively high and well outside the acceptable gradings defined by Tarling and Dobson (1995), it was not possible to apply the corrected mean site direction to the Clark calibration curve and produce a reliable date range in the conventional manner (Chapter 2, section 2.6). Figure 4.42 shows the directional data superimposed on the calibration curve and a summary of the results is given in Table 4.4.

4.7.3.4 Discussion

All of the Penguelan PSS4 sample magnetisations were measurable but exhibited low magnetic intensity. The hearth material from which the dating samples were obtained appeared to be heat affected both visually and in comparison with the magnetic susceptibilities of similarly heat affected clays at another high temperature furnace site (section 4.8.1). The stereo plots (Figure 4.41) indicate a considerable amount of directional scatter, both in the initial measurements and the subsequent sample demagnetisations. The reasons for the magnetic behaviour of the four pilot samples are speculative and may be difficult to explain, but could include variations in the mineral content of the basic clay material and the way it has reacted to the heating/cooling cycles of the hearth operation. The stability indices (SIs) of these pilot samples suggested that the hearth material from which the AMD samples were obtained was "magnetically stable".

Two levels of confidence errors are shown in Table 4.4, α_{95} and α_{68} (the error at 68% confidence level). Both are excessively high and may have been caused by a number of factors including mineralogical and magnetic characteristic variations in the hearth material, as well as the possibility of significant physical disturbance of the hearth at any time up to excavation, and the potential for disturbance during excavation and during sample acquisition; the dating samples could be considered as not being strictly *in situ* due to the possible disturbance. The combination of variations and disturbances could account for the initial sample directional scatter noted above.

The corrected mean directions were applied to both upper and lower calibration curves (Figure 4.42). However, the consequence of a combination of low initial magnetic intensities and wide directional scatter is a low confidence in the calculated mean direction, which when applied to the calibration curve could not produce a reliable archaeomagnetic date range.

4.8 General discussion

Both Hetherington (1978) and Smith (2006a) showed that under experimental laboratory conditions, temperatures of 800°C or more were required to produce the different types of lead slags comparable to those of the early technology sites. If similar temperatures occurred during bole/bale or blackwork oven smelting, or at least over 700°C and up to 900°C (the limit considered to be achieved in semi-controlled bonfire technology: G. McDonnell pers. comm.), then some significant enhancement to the ground beneath the bole/bale or oven might be expected, including thermally induced remanence; this expectation is on the assumption that the geology of the site allowed enhancement to take place, i.e. there was sufficient iron oxide content in the ground for measurable enhancement to occur. The magnetometer surveys conducted at Grinton Smeltings and Totley Bole Hill both showed low values of magnetic enhancement to the presumed areas of the smelting activity and no remanent magnetism. The possible causes of these magnetic characteristics are that the ground surface and underlying geology at both sites have a low iron oxide content, and/or that the operating temperatures were not achieving 700°C. With the evidence of the amount of slag remaining at both sites, it seems certain that operating temperatures in the range noted above were achieved, which suggests that the iron oxide content of each site's geology was indeed low. Unfortunately, the preconditions of access to the Grinton Smeltings site and the scheduled ancient monument status of Totley Bole Hill prevented acquisition of soil and geological samples for magnetic susceptibility, fractional conversion and heating measurements.

Operating temperatures in boles and bales could be expected to reach over 700°C. Although not actually specified, Gill (1992) implies that the operating temperatures of blackwork ovens are similar to those in ore and slag hearths, i.e. around 1000°C. As they were constructed directly on the ground like boles or bales, blackwork ovens could be predicted to cause a similar magnetic enhancement and potential thermoremanence. Although the operating temperatures of ore and slag hearths were between 1000 and 1200°C, due to their construction there was no direct contact with the ground and, therefore, little or no magnetic enhancement as a result.

As Vernon *et al*. observe (1999), whilst the iron smelting process can broadly be grouped into direct and indirect methods, as characterised by the iron smelting furnace and blast furnace technology (respectively) and which have a basic chronological order or sequence, there is no exact equivalent for lead smelting. The limited evidence available from medieval and post-medieval lead smelting sites would suggest that there are regional variations in both the smelting techniques and structures in these periods. A good example of this time-technology mismatch or overlap is the continuation of bale smelting in the Yorkshire Dales at the same time as the widespread use of ore and slag hearths in the Peak District smelt mills. At the two sites investigated in this research (Grinton Smeltings and Totley Bole Hill), the magnetometer surveys have shown that remanent magnetism has not been acquired and, consequently, no archaeomagnetic date can be obtained. Thus, to allocate a specific lead smelting structure to a particular time period could be almost impossible without recourse to other dating techniques.

4.9 Conclusions

The Grinton Smeltings and Totley Bole Hill surveys have both demonstrated that it is feasible to conduct geophysical prospection over archaeological medieval/post-medieval lead smelting sites, and that the traces of the smelting activities do exist to an extent which can be identified. However, there were no indications of remanence recorded on either site; if this outcome is repeated at other medieval/post-medieval lead smelting sites, then archaeomagnetic dating of such industrial sites may not be possible and other dating methods will be necessary.

For ease of use and maximisation of data recording, a magnetometer survey employing a fluxgate gradiometer has been shown to be the most appropriate survey method at both sites and may also be suitable at other similar locations. The earth resistance survey method was shown to be of limited use at both survey sites due to the apparent lack of distinct anomalies attributable to smelting activities, and although this may be the case at other lead smelting sites the technique should still be used. As noted above in section 4.7.2, magnetic susceptibility surveys were not undertaken due to the variable nature of the ground surface over the Grinton Smeltings and Totley Bole Hill sites. However, the magnetic susceptibility survey technique should still be considered for use at other lead smelting sites as a norm to complement magnetometer surveys, but subject to individual site ground surface considerations.

As a consequence of this study into the magnetic characteristics of medieval/post-medieval lead smelting sites, suggestions for further investigations are made in Chapter 12, section 12.2.2.