Chapter 6.0 A comparison of the Magnetic Susceptibility of slag

6.1 Introduction

Magnetic susceptibility is the degree to which a material is magnetized when subjected to a magnetic field. It has been recognised since the 1950s that magnetic susceptibility could be used to identify changes in topsoil (Le Borgne 1955). Most research however has been conducted on soil types with very little emphasis on industrial activity. The principles behind magnetic susceptibility have been described in Chapter 2.2.3.

The intense heat associated with an operating kiln, furnace or oven will alter the magnetic susceptibility of the clay from which the furnace is built or lined. The high positive magnetic response that such structures generate is the direct consequence. To a lesser extent this can also be applied to residues from industrial activity. At Kyloe Cow Beck, Bilsdale, North Yorkshire, for example, magnetic inclusions in the slag were attributed to ferro- and ferrimagnetic material occurring as roasted ore, or partially reduced ore combined with haematite and magnetite, respectively. Iron prills were also identified (Powell *et al*. 2002).

The slag from the Timberholme, Bilsdale, North Yorkshire suggested both bloomery and high-bloomery processes were conducted there with high (74.8%) and low (5.3%) iron oxide and magnetic susceptibility values of 77 and 40 x 10^{-7} m^3/kg respectively (Vernon *et al.* 1998a – Table 1). It was realised from these variations that it might be possible to use magnetic susceptibility as a rudimentary method to identify slag types (Vernon 1995, 99).

There are very few published works that refer to the magnetic susceptibility of slag. Al-Mussay (1990) recognised that the magnetic susceptibility of iron slag could be used to differentiate between ‘old’ and ‘recent’ slag. The descriptions would suggest that ‘old slag’ and ‘recent slag’ are equivalent to bloomery (dark grey and porous slag) and charcoal-fired blast furnace (dark green and glassy slag) type slag, respectively. The conclusion was that metallic ‘drops’ of iron were the main cause of magnetisation in the ‘recent’ slag, whilst Magnetite was the main magnetic component in the ‘old’ slag.

Powell *et al*. (2002) have also made a detailed study of the magnetic responses of material from the Kyloe Cow Beck bloomery site and have identified the principal components that produce the magnetic anomalies in iron slag. The study also provided details of the magnetic susceptibility of slag and furnace lining. The bloomery slag mass specific susceptibility ranged from 16.8 to 296.0 x 10^{-7} m^3/kg (Powell *et al*. 2002, Table 2).

Vernon *et al*. (1998a) compared the magnetic susceptibility of slag from bloomery, high-bloomery and charcoal-fired blast furnaces. This research has since been extended to compare the magnetic susceptibility of iron slag with those produced by lead (Vernon *et al*. 1999a) and copper (Vernon *et al*. 2002) smelting and the findings from this research are included in the following sections. The purpose of the study is to try to characterise the magnetic signature of different slag types that have been produced by different smelting processes.

6.2 Equipment and methods

The equipment and method used to measure the mass specific magnetic susceptibility of material in the laboratory has not changed significantly since reported in detail by Tite and Mullins (1971, 210) and elaborated on by Scollar *et al*. (1990, 408 – 411) and Clark 1990, 102-104). The recent research by Powell *et al*. (2002) describes the measurement of mass magnetic susceptibility measurements in detail and states that the technique, using the AC bridge, has a measurement error of ±3%. The same equipment was used in the current research.

For the research, slag samples were randomly selected from different areas of individual slag dumps to try and represent the likely magnetic susceptibility ranges present. A wide variety of British iron, lead, copper and tin smelting sites that employed different smelting techniques have been sampled. Apart from the iron slag, which has been produced from a variety of ores, but predominantly siderite, the smelted ores for lead, copper and tin are mainly galena, chalcopyrite and cassiterite, respectively, albeit from a variety of locations. On tin smelting sites it has not always been possible to find large quantities of slag.

Slag samples were washed in cold water and scrubbed to remove soil and other superficial material. Deep gas bubbles in the slag were probed with a wooden toothpick to clear out soil and debris. The samples were then placed on newspaper and allowed to dry naturally. The slag was also inspected closely for any under-surface inclusions of extraneous material that had adhered to the slag from, for example the tapping channel during cooling. Once dry the samples were weighed (to two decimal places) and placed in a sealed polythene sample bag.

The slag sample was then placed in the wire coil of the balanced AC susceptibility bridge. The bridge required calibration at the commencement of each measuring session using 50g samples of a substance with a known contrasting magnetic susceptibility, for example manganese sulphate (81.2 x 10^{-8} m^3/kg) and high alumina cement (716 x 10^{-8} m^3/kg). The data was inputted into a *Microsoft Excel* spreadsheet and the magnetic susceptibility was calculated for each sample. Where possible a number of samples from each site were measured. The main advantage of using this method was consistency and allowed the slag data to be reliably compared and their trends evaluated. If used as a field method mass specific magnetic susceptibility sampling is slow.

Published magnetic susceptibility measuring methodologies refer to soil measurements, for example Scollar *et al*. (1990, 403). The wide magnetic susceptibility variations of the slag, ore and furnace materials meant that it was impractical to test a standard weight. As a general rule slag samples were usually no larger than 2 to 3 cm in size. Larger samples would not fit into the AC bridge coil. Material with a high magnetic susceptibility may take the instrument reading off the scale. To overcome this problem, the solution was to reduce the size of the sample and re-measure.

In this study, samples of slag have been taken where possible from the different technological stages for smelting each metal. Ore samples were also tested together with any available samples from intermediary stages, for example roasted ore, to illustrate the magnitude of the magnetic susceptibility changes that occur during the smelting processes.

6.3 Iron slag

Iron minerals are probably the most complex of the four metals examined and are the main contributors to the magnetic susceptibility of a material. The study records the magnetic susceptibility from various ores, roasted ores and the slag from different iron smelting processes, to show how the magnetic susceptibility changes during smelting. Where known the iron oxide content of the slag has been noted. It may represent the component responsible for a high magnetic susceptibility. However a high percentage of iron oxides cannot always be regarded as a factor that elevates the magnetic susceptibility as they may occur as silicates.

The mineralogy of ironworking slag has been extensively researched (Morton and Wingrove 1971, 1972; Fells 1983; McDonnell 1986; Finney 1997b; Elliott 2001). Iron smelting slag consists of three main phases, iron silicate (usually fayalite ($2FeO.SiO_2$)), iron oxide (normally wüstite (FeO)) and a glassy matrix. Other minor mineral phases may be present for example, leucite ($K_2O.Al_2O_3.4SiO_2$) and hercynite ($FeO. Al_2O_3$) (Fells 1983, 95 -100). The relative proportion of the phases is dependant on many factors that includes, composition and the cooling regime. Fayalite has a magnetic susceptibility that varies from 0.5 to 13 x 10^{-7} m^3/kg. Wüstite has a magnetic susceptibility that ranges from 10 to 100 x 10^{-7} m^3/kg (Powell *et al*. 2002, Table 3).

Metallic iron exhibits ferromagnetic properties, while the primary oxides magnetite and haematite are ferrimagnetic and weakly anti-ferromagnetic, respectively (Powell *et al.* 2002). Sideritic ores are more complicated as they are an iron carbonate of sedimentary origin with a complex mineralogy. Hounslow (2001) has shown that there are no superparamagnetic single domain or multi-domain ferrimagnetic particles in siderite. The susceptibility is due to the presence of paramagnetic minerals. Figure 6.3.1 compares iron ore from a variety of sources. Magnetite has the highest magnetic susceptibility range (2568 to 7967 x 10^{-7} m^3/kg). The Cumbrian haematite (2.46 to 3.70 x 10^{-7} m^3/kg) produces slightly higher values than siderite (2.90 to 6.73 x 10^{-7} k m^3/kg). Cumbrian haematite is the source ore for the Duddon charcoal-fired blast furnace slag. The remaining sites smelted siderite from various sources in the Carboniferous Coal Measures (Huglet and Crofton, South and West Yorkshire, respectively) and the Lower and Middle Jurassic (Staithes, North Yorkshire and Corby, Northamptonshire). In the North Yorkshire Moors area the only complete sequence of outcropping iron ore is confined to the foreshore and cliffs at Staithes (Rawson and Wright 2000,16–24). Samples were collected from the Avicula, Two Foot, Pecten and Main seams and the weathered material was trimmed off the specimens before testing.

Magnetite is usually formed in the roasting process. The magnetic susceptibility of roasted siderite listed in Figure 6.3.1 ranges from 351 to 1281 x 10^{-7} m^3/kg and approaches the magnetic susceptibility of magnetite. These data are included on Figure 6.3.1.

The iron slag used for measuring magnetic susceptibility was collected from geophysically surveyed sites, but other sites have been included for comparison. The sites are grouped into bloomeries, high bloomeries, charcoal-fired blast furnaces and finery / chafery complexes.

6.3.1 Bloomery Slag

The bloomery slag has been collected from five areas, North Yorkshire, Northamptonshire, Greater Manchester, South and West Yorkshire. The majority of sites are probably medieval associated with monastic houses, mainly the Cistercian order. The likely ages of the Ridlington, Fineshade, Crofton and Wentworth sites are not known. The data are shown in Figure 6.3.2.

In the medieval iron smelting (bloomery) slag from Bilsdale, North Yorkshire, fayalite dominates, with small amounts of fine dendritic free iron oxide (wüstite) present in a glassy matrix. The Bilsdale slag also contains hercynite (Finney 1997b; Elliott 2001). Nearly all the slag analyzed contains finely disseminated, very small (microns?) prills of iron. Occasionally there are larger iron prills.

Most of the sampled iron bloomery sites are found near the outcrops of sideritic ironstone. North Yorkshire, Northamptonshire and Rutland sites are linked to Lower and Middle Jurassic deposits and the remainder with the Carboniferous Coal Measures. The sampled bloomery slag falls within the 10 to 50 x 10^{-7} m^3/kg range but there are notable exceptions, for example Kyloe Cow Beck (207 x 10^{-7} m^3/kg). The variations in magnetic susceptibility can be related to the percentage of iron oxide, but this can be elevated by, for example, the presence of iron prills (Vernon *et al*. 1998a). All the tested samples are tap slag.

On Figure 6.3.2 sites F1 to F3 are all located in Bilsdale, North Yorkshire, on land once controlled by Rievaulx Abbey. Kyloe Cow Beck (F1) samples were taken from both the stream bank exposures and the excavation. Powell *et al*. (2002), note that partly reduced ore / magnetite and iron prills occur within the Kyloe Cow Beck slag that could account for the high values. For example, the type 1 slag, regarded as a 'typical' tap slag, and type 3 slag contained 34% and 65% iron oxide, respectively (Powell *et al*. 2002). A value of 1500 x 10^{-8} kg/m^3 produced by the latter was attributed to the presence of partly roasted ore in the sample (Powell *et al*. 2002). The Hagg End site (F2) lies adjacent to the River Seph close to a pit where ore might have been extracted. The Grange (F3) consists of a low-lying slag mound. One analysed sample of tap slag from the Grange contained 44.7% iron oxide (Vernon *et al*. 1998a).

Sites F4 to F8 have been used for comparison with Bilsdale samples and are located in the Ryedale / Snilesworth area, to the west of Bilsdale on Byland Abbey land. Cow Wath (F8) is located on a hillside and the tip contains abundant roasted ore. The slag is also 'frothy' in morphology unlike the tap slag that exhibits flow structure and dominates the other slag heaps. The slag is reported to contain 38.9% iron oxide (McDonnell 1972). The remaining sites (F4 to F7) lie on, or close, to the Ryedale valley bottom. The Thack Wath (F5) slag contained 45.1% iron oxide (McDonnell, 1972). The Castleshaw (F9) and the Myers Wood (F10) furnaces may have similar monastic origins. Both areas, albeit on opposite sides of the Pennines were once medieval granges of Roche Abbey, near Maltby, South Yorkshire (Redhead 1992, 1993 and Vernon 2001b). The source ores were sideritic mudstones and ironstone from the Lower Coal Measures. The Cockley Hill site (F11) at Kirkheaton, Huddersfield occupies a similar geological horizon to Myers Wood and again is thought to be monastic (SMR Record, West Yorkshire Archaeological Services, Wakefield). The site occupies a spur between two streams and has undergone severe disturbance and evidence for smelting is limited to a thin spread of tap slag.

The two Margery Wood sites (F12 and F13) are close to the outcrop of the Lower Coal Measures Tankersley Ironstone, north of Cawthorne, South Yorkshire. Earliest documentary evidence records iron mining in the area in the 14^{th} century during a period when various monastic houses had granges in the area specifically to work the ironstones. The slagheaps are extensive and lie adjacent to a beck. It has been suggested that the site was water-powered (Umpley 2000, 96 - 97).

Samples F14 to F15 were all collected close to the outcrop of the Jurassic Northamptonshire Ironstone. The age of the sites are not known.

6.3.2 High Bloomery

Timberholme (Figure 6.3.2 F17), Bilsdale, North Yorkshire, represents the only high bloomery site positively identified in Britain. The slag was shown to have the morphology of a bloomery tap slag but a chemical composition similar to that produced by a charcoal-fired blast furnace (Vernon *et al*. 1998a). The slag from the high bloomery is currently under investigation at the Department of Archaeological Science, University of Bradford but initial mineralogical analyses has identified two slag types. The first has a low iron content (5.3%FeO), and is glassy. The second type with a high magnetic susceptibility has a high iron content (75%FeO), and a microstructure dominated by iron oxide dendrites (Vernon *et al*.1998a; Finney 1997b).

The magnetic susceptibility of Timberholme slag ranges from 6.7 to 77.9 x 10^{-7} m^3/kg. The two extreme values represent both modes of operation. The low and high values from the slag are produced by the blast furnace and bloomery modes respectively. The high value is generated by metallic prills (Vernon *et al*. 1998a).

6.3.3 Charcoal-fired Blast Furnace

The magnetic susceptibility has been determined from slag samples from four charcoal-fired blast furnace sites (Figure 6.3.2 F18 to F21) and compared with slag from a modern blast furnace at Redcar (F22). The Duddon slag is derived from smelted Cumbrian haematite and the Rievaulx slag from the Lower and Middle Jurassic ironstone have relatively similar magnetic susceptibilities. However slag from Rockley is higher by a factor of 10 when compared to that from West Bretton. Both furnaces smelted the Tankersley ironstone mined from the Lower Coal Measures (Raistrick 1939).

Charcoal-fired blast furnace slag is glassy with numerous iron prills (Finney 1997). Only a small number of samples from each site have been tested, so the high values may be generated by iron prills within the sample but another explanation might be that the Rockley furnace was not being run efficiently. Rockley is unusual in that it has a third archway into the furnace but its purpose is not clear (Riden 1993, 105). It might also suggest that some experimentation was taking place in the smelting process.

Modern blast furnace practice is clearly more efficient, returning values of only around 5.0 x 10^{-7} m^3/kg. The iron ore smelted at Redcar is obtained from a variety of global sources.

6.3.4 Finery and Chafery

The Rye House (Figure 6.3.2. F23) and Forge Farm (Figure 6.3.2. F24) sites at Rievaulx, North Yorkshire are finery and chafery sites, respectively (McDonnell 1972; Walline 1997). Despite geophysically surveying the area around Rye House in detail, the only evidence for metalworking is a tentative waterpower system and a dump of furnace bottoms on the side of the River Rye from which the samples have been taken. It is not known if those furnace bottoms were dumped from elsewhere (McDonnell 1972 and Vernon *et al*. 1998b). The high values (361 to 381 x 10^{-7} m^3/kg) would suggest that the slag has high iron content. The lower range of values at Forge Farm (27.1 to 91.0 x 10^{-7} m^3/kg) may suggest a more efficient operation.

6.4 Lead slag

Samples of lead slag have been taken from smelting sites in the Yorkshire Pennines and several locations in Wales. Apart from the papers that report on the current research (Vernon *et al*. 1999a and Vernon *et al*. 2002) that compare the magnetic susceptibility of lead, iron and copper slag, there are no other known publications offering such comparisons.

Un-smelted galena often occurs as a main component or as inclusions in the grey lead slag from bale sites (*personal observation*). At Windegg, Arkengarthdale for example, two samples of galena rich slag produced a mean value of 0.31 x 10^{-7} m^3/kg (Figure 6.4.1). Pure galena has a magnetic susceptibility of 0.44 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 190), suggesting that the Windegg samples were contaminated.

Iron does not usually occur chemically combined with galena but may be present commonly as iron pyrites or siderite in the mineral vein (Gill 1992b; Ixer 2003). Analysis of lead slag comes from a variety of published sources. Hetherington (1979) provides numerous analyses of lead slag frequently quoted by other researchers. McDonnell *et al*. (1992) record that grey bale slag from Grinton, Swaledale contained prills of lead and a trace of iron (<0.5%?). Murphy (1992) comments that white coated slag from Fell End Boles, Arkengarthdale contained minor amounts of iron. Murphy (1992) also records that dark-grey black slag from a simple ore-hearth smelter at Hoggett Gill, Patterdale, Cumbria, contains minor amounts of iron, occurring predominantly as silicates. Generally bale / bole slag has an iron oxide content of less than 1%, and similar to iron slag it may be a component of the glassy phase and exhibit non-magnetic properties.

The magnetic susceptibility values of lead slag recovered from the geophysically surveyed sites (Grinton, Dacre and Marrick) are shown in Figure 6.4.1. Magnetic susceptibility values of lead slag from other sites in Northern England and Wales are included for comparison.

6.4.1 Bale / Bole sites

Bole / bale sites (Figure 6.4.1) are generally regarded as being medieval (Gill 2001) and the smelted ore was generally selectively prepared by hand (Vernon *et al*. 2002). The Grinton (P1), Windegg (P2) and Slei Gill (P3) samples were taken from substantial scatters of grey and black slag at recorded hillside bale sites in Swaledale and Arkengarthdale, North Yorkshire (Vernon *et al*. 2002; Murphy and Baldwin 2001). None of these sites are dated. In contrast, the Dacre (P4) bale site lies on the valley floor of Nidderdale and might represent a stage in lead smelting technology that falls between the bale and the ore hearth techniques. Slag samples were taken from a thin layer of grey lead slag and slag rich sediments exposed about 0.3m below the surface in the side of the adjacent beck. The age of the site is not known but it certainly pre-dates the 19th century (Blacker *et al*. 1996, 145; Blacker, *pers*. *comm*., 1998; Vernon *et al*. 1999a).

6.4.2 Ore Hearths

Data from ore hearths are shown on Figure 6.4.1. The 18th century Llangynog (P5), Powys smelt mill built between 1705 and 1714 probably contained an ore hearth (Williams 1985, 69). A sheep enclosure has been constructed on the mill site. Slag samples were taken from a layer of black glassy slag. The mills at Blakethwaite (P6), and Whashton (P7), Swaledale, North Yorkshire also employed ore hearth technology. Blakethwaite commenced smelting in December 1819 with two ore hearths. A roasting furnace was added later (Raistrick 1975b, 93 - 94). The Whashton (also known as Hartford or Gilling) lead mill, located on a major packhorse route from Swaledale, is possibly older. Documents suggest that it was operating on the site in 1671 (Raistrick 1975b, 29 - 32) or even earlier (Gill 2001, 159). Samples were taken from the dump in front of the mill. The Beldi Hill (P8) mill also in Swaledale in addition to an ore heath contained slag and ore-roasting furnaces (Gill 2001, 44). Raistrick (1975b, 71) indicated that the mill was built in two stages, the ore hearth in 1771 and the slag hearth seventy years later. Samples were taken from the general slag scatter around the mill.

6.4.3 Cupola / Reverberatory Furnaces

Slag samples have been recovered from three early cupola sites (Figure 6.4.1). Marrick

(P9), Swaledale started operating in 1701 and pioneered the use of reverberatory furnace technology in the Yorkshire Dales (Gill 2001, 146). Grassington (P10), commenced operations in 1793 probably ceased operating in 1882 (Clough 1962, 77; Bassham 1992, 37; Gill 1993, 122) and Gadlys (P11), Flintshire, was operating in1703 / 1704 (Lewis 1967, 358) but was pulled down in 1786 (Williams 1997, Figure 58). The new Dee Bank lead works (operated from 1870 to 1927) was one of the last major lead smelters in Flintshire and employed a variety of smelting techniques (Williams 1997, Figure 63).

Figure 6.4.1 compares the magnetic susceptibilities from the different processes. The magnetic susceptibility values for the bale furnace slag and the simple ore hearths all fall within a tight range (0.31 to 2.2 x 10^{-7} m^3/kg). However, slag from mills that utilized more complex processes produce higher values, for example Dee Bank (P12) and this may be due to incomplete or inefficient mineral processing, an aspect that will be discussed later.

6.5 Copper slag

Copper smelting sites, compared with those of iron and lead, are relatively scarce in Britain. The most common copper ore in Britain, chalcopyrite ($CuFeS_2$), is found in mineral veins in Cornwall and Devon, North Wales and Cumbria. There are also several significant copper mining areas flanking the Pennines, at Ecton (Staffordshire), Alderley Edge (Cheshire) and the Richmond area (North Yorkshire). The Alderley Edge deposits are different as the principal copper ore is malachite ($CuCO_3.Cu(OH)_2$), a secondary replacement deposit disseminated throughout the Triassic sandstones and conglomerates. The malachite concentrates in jointing to form mineral veins, for example Engine Vein, where there is considerable evidence for Bronze Age mining (Carlon 1979, 29 and 37).

Chalcopyrite is relatively rare on surface mine dumps but two samples from the Beddgelert area, Gwynedd produced a mean reading of 178.2 x 10^{-7} m^3/kg (Figure 6.5.1). However, chalcopyrite has a mass magnetic susceptibility of 0.55 to 10 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 191), a value considerably lower than that recorded on the Beddgelert samples suggesting that the material was not pure chalcopyrite.

There are very few examples of early copper smelting slag from Great Britain (Bachmann 1982). Pleiner (2000, 12) comments that early copper smelting slag "*was identical with that produced later by bloomery iron-smelting, since it had the familiar fayalite and wüstite phases, with a high iron content and contained no more than traces of copper..*". The mines of Cornwall and Devon were the largest producers of copper ore in Britain in the 19th century. The earliest evidence for copper smelting is confined to 16th century documents recording the activities of German mining and copper smelting expertise in Cornwall, South Wales and Cumbria (Pascoe 1981, 19 and Barton 1978, 10). Copper slag samples used in this study are therefore from six post-medieval smelters from various British locations.

The multiple smelting procedures (6 to 10 stages) to remove iron, via the slag, from the copper are reflected by the varying amounts of iron oxide found in the slag, but from a geophysical consideration may not be present in a magnetic form. The 'Welsh Process' utilizing the reverberatory furnace was used from about 1700 (Tylecote 1984, 129) and was employed on some of the sampled sites, for example Middleton Tyas. Tylecote (1984, 131) reproduces an analysis of Swansea copper slag from different smelting stages. The data originally published in 1852 /1853 show that ‘waste slag from the ore furnace’ (the first stage) contained 28.5% iron oxide. Successive stages produced slag with 36% to58% iron oxide.

Figure 6.5.1 compares the magnetic susceptibility values from the geophysically surveyed sites (Ellastone and Whashton) and from several other sources. Ellastone (C1) is the earlier of the two sites; the smelter was built in 1660/1 but only operated for 26 years. The land to the east of the ‘*Copper Mill Yard*’ is referred to as ‘*Copper Roasting Piece*’ suggesting two components to the site (Porter and Robey 2000, 249). Slag samples were all obtained from the banks of the stream that bisects the site. The Whashton copper mill (C2) located to the north of Richmond, North Yorkshire dates from 1728. Samples were taken from prominent slag dumps. The slag is also known to contain traces of copper (Raistrick 1975b, 110 and Hornshaw 1975, 108).

There are no visible remains of the nearby Middleton Tyas smelt mill (C3) or the slag dumps. The samples were removed from a brick shaped block of slag used for walling, very common in the Myddleton Tyas area. Two sites were sampled in the vicinity of Parys Mountain, Anglesey. Samples (C4) were recovered from dumps on the west side of the narrow creek that forms Amlwch’s harbour. Samples (C5) were taken from blocks of slag near a smelter thought to be late 19th century on the south side of Parys Mountain (Vernon 1996, 38 and 43). The Coniston (C6) samples were taken from a slag dump associated with a smelter that was commissioned during 1893 (Holland 1987, 214).

6.6 Tin slag

Cassiterite, the primary tin ore, was economically important in southwest England. Mineralogically, tin slag is usually glassy and contains prills of tin and unreacted granitic inclusions (Malham *et al*. 2002). Samples of ore produced a magnetic susceptibility of 21.6 x 10^{-8} m^3/kg comparing favourably with the actual value of 16 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 190). The magnetic susceptibility results for tin slag are shown in Figure 6.6.1. Tin slag has been sampled from three sites. The samples from Crift (Buckley and Earl 1990; McDonnell 1993; McDonnell *et al*. 1995; Malham *et al*. 2002) were probably of alluvial (tin-streaming) origins (Collins 1878, 43). The elevated location of Crift precluded waterpower and it is presumed that the ore was sorted and dressed by hand. The samples (S1) were taken from the dump that contained about five tonnes of tin smelting slag (Malham *et al*. 2002). Two blowing house sites were also sampled, Coombe – Millpool (S2) on Bodmin Moor (Rose and Herring 1990) and Upper Merrivale (S3) on Dartmoor (Greaves and Newman, 1994). Typical of blowing house sites there were no obvious slag dumps and samples, when found, were extremely small, often not more than 0.4mm in size.

6.7 Discussion on the magnetic susceptibility of slag

Detailed examination of slag composition can lead to an assessment of smelter efficiency by virtue of their metal content. However, slag analysis has to be done in the laboratory using specialized equipment. Fortunately the simple procedure of measuring the magnetic susceptibility of slag may also give some indication of slag type, when considered with other information, for example where it was found. Care should be taken when drawing comparisons between the iron oxide content of a slag with the magnetic susceptibility, as not all forms of iron oxide are magnetic. However it can serve as an indicator.

The magnetic susceptibility value of iron slag has been shown to follow certain trends based on the complexity of the smelting process that produced it (Vernon *et al*. 1998a) and are to some extent confirmed by the comparisons on Figure 6.3.2. Shaft furnaces or bloomeries may produce slag with over 40% iron oxide and a corresponding high magnetic susceptibility. In contrast, the more efficient charcoal blast furnace slag may contain approximately 5% iron oxide. The slag from the high bloomery at Timberholme, which is thought to be capable of switching from a bloomery to a blast furnace, lies between these two distinct processes. The modern blast furnace at Redcar is even more efficient, with the magnetic susceptibility value lower than that for the charcoal blast furnace. Recent research (Powell *et al*. 2001) would indicate that the magnetic susceptibility value is also dependant on the percentage of iron prills within the slag, particularly those produced by a blast furnace. However, as stated previously, the percentage of iron oxide cannot be regarded as an indication of the magnetic susceptibility, or the likely responses on a fluxgate gradiometer survey, because the iron oxide content may represent non-magnetic forms that are principal components of the slag's glassy phase. The chemistry and mineralogy of slag is complex and slag formation is dependant on composition and cooling regimes.

Pure lead ore commonly in the form of galena (PbS) contains virtually no iron. However iron minerals, for example iron pyrites (FeS), may occur with galena in the mineral vein. The mining, and then the manual ore dressing that provided the ore for bale smelting, would have been very selective in reducing the inclusion of such minerals. The low magnetic susceptibility readings for slag from bale sites tend to fall within a very tight band (Figure 6.4.1). It is probable that this was also the case for small ore hearth operations as slag from this process can produce similar magnetic susceptibility readings to bale slag. However, as mineral processing became more complex, employing gravity separation techniques, it would have been inevitable that iron rich gangue minerals remained mixed with the lead ore. The high magnetic susceptibility values associated with larger smelt mills may possibly be attributed to this explanation. The very high magnetic susceptibility value produced by the Marrick slag is exceptional. Iron may have been introduced into the process in several ways. Firstly it was one of the first reverberatory lead smelting mills in the country and it is possible that the process was subjected to experimentation. Secondly the mill was also smelting ore from a variety of sources (Gill 2001, 147), and some ore batches might have contained high percentages of iron rich mineral. The use of waterpower to operate complex ore-dressing machinery probably coincided with the mechanization of smelting.

A fundamental requirement of the copper smelting process was the necessity to run off the iron in the slag. Both the Ellastone and Whashton samples appear to bear this out with resulting magnetic susceptibility values higher than those for iron slag. However it is reasonable to assume that the magnetic susceptibility value will vary depending on the processing stage that produced the slag. Hetherington (1979, 42) comments that '*a prominent feature of copper smelting slag is that due to the oxidising conditions present, especially in the converting operations, magnetite is often formed in some quantity.*', a point reinforced by Pleiner (2000, 12). Given some of the higher magnetic susceptibility values associated with copper slag then this explanation may have credence.

The magnetic susceptibility of tin slag is low compared to iron and copper smelting sites. Analysis of tin slag (Malham *et al*. 2002, Tables 1 and 4) shows that the majority of blowing house slag (mean 12.6% iron oxide) sampled has a higher iron oxide content than those from Crift (mean 6.5% iron oxide). It is possible that the magnetic susceptibility is following a similar pattern albeit based on very few samples. Blowing house technology was probably not as selective as the hand-dressing methods employed at Crift and iron minerals could enter the smelting process, especially if vein tin ore was added (Gerrard 2000, 129 - 139). Another reason for the higher iron oxide may result from the common practice to crush and re-smelt tin-slag to release any residual metallic tin and that may concentrate other minerals in the slag. Geological variations may also influence the amount of iron minerals in the smelted ore (Malham and McDonnell, *forthcoming*). A stream sediment survey (Nichol *et al*. 1971) that covers the northern parts of Bodmin and Dartmoor Moors reports '*moderate contents of 1.5 to 3.0% of Fe_2O_3 predominate on the Dartmoor granite except near the western contact where there are a number of high values'*. Bodmin granite stream sediments may have lower values, but the sampling is not as intense as at Dartmoor to draw a valid conclusion.

With the introduction of the reverberatory furnace came a period of experimentation. In addition there was often more than one stage to the reverberatory process that produced different slag, for example the 'Welsh Process' for copper smelting (Hughes 2000, 25). Slag was sometimes reintroduced as a fluxing agent (Hunt 1863, 652). With so many variables in this technique it is unlikely that reverberatory slag can be reliably characterized by using magnetic susceptibility measurement.