Chapter 5.0 Metal smelting technology and structures together with geophysical data from surveyed examples

5.1 Iron

5.1.1 Introduction

Geologically, the primary ores of iron are magnetite (Fe_3O_4) and haematite (Fe_2O_3) and contain 72.4% and 70% iron respectively. Secondary iron ores are siderite ($FeCO_3$) with 48.3% iron, goethite (FeO(OH)) with 62.9% iron, associated with limonite (approximately $2Fe_2O_3.3H_2O$) with 59.9% iron (Read 1962, 482 - 490). Bog iron ore is a loose and porous form of limonite (Read 1962, 489). Resources of iron ore are common throughout Britain (Anon 1918, 9). However in terms of exploitation it is the sideritic and limonitic ores that are of primary importance with significant deposits of the former ore occurring in the Carboniferous Coal Measures and the Lower and Middle Jurassic. Iron-smelting technology has been extensively studied with many of the technological changes well documented and understood (Schubert 1957; Tylecote 1984, 1990; Pleiner 2000).

The present research has examined a variety of archaeological iron-smelting sites by geophysical survey. The sites cover different technological stages and vary from those using simple shaft furnaces through to water-powered charcoal-fired blast furnaces. Ancillary structures and processes have also been considered including slag dumps, charcoal production and storage areas, water leats and forges.

5.1.1.1 Smelting Techniques

Iron-smelting technology has been subdivided into two distinct processes, *Direct* and *Indirect* (Schubert 1957; McDonnell 1995a and 1995c).

The *Direct* or the Bloomery process produces a malleable iron (often mistakenly described as wrought iron). Tylecote (1984, 86) and Pleiner (2000, 131 to 140) describe the bloomery process throughout Britain and Europe, respectively. The numerous examples they describe demonstrate that the bloomery shaft furnace and related structures, for example ore roasting sites, can vary considerably in both form and dimensions. The furnace most commonly encountered in Britain is a simple shaft furnace (See Figure 5.1.1 for a description of the process). When constructed it is generally cylindrical and probably not more than 2.0m in height with an internal diameter of 0.3 - 0.5m. The wall of the furnace, or lining is composed of clay. The external diameter may often be up to 1.0m. They were often built into a hillside that facilitated charging. This factor, combined with thick furnace walls (>0.2m), helped to retain heat. However, McDonnell (1995a) suggests that a furnace should be regarded as a shaft of varying dimensions, as there are no set rules. An intact furnace is a very rare exception in an archaeological situation and remains may just consist of a furnace base with traces of the wall. The full height can never be ascertained.

A mixture of charcoal and iron ore is put into the furnace through the top opening and is fired. The highest temperatures (> 1200 ºC) occur towards the base next to the tuyere, the point where air is blown into the furnace. Impurities melt, mobilize and form slag. The iron forms a "bloom", a mixture of iron and slag that adheres to the side of the furnace. The hot bloom is then removed either via the tap arch or through the top opening and is then refined by repeated re-heating and hammering to produce a malleable iron.

Evidence for shaft furnace type technology can be found in most iron producing areas of Britain. In the simplest and earliest forms of the furnace, the slag pit, for example at North Jutland, Denmark, c210AD (Tylecote 1984, 54), the slag remained *in situ*. Earliest evidence in Britain (Iron and Romano-British Ages) comes from plano-convex slag furnace bottoms formed *in situ* in a shallow depression at the base of the shaft (Tylecote 1990, 130). At Welham Bridge, Humberside (Clogg 1999, 89), measurements on plano-convex material suggested that the furnaces had an internal diameter of 0.3 to 0.4m and the depression was about 0.2m deep. At Crawcwellt, Merioneth (Crew 2002, 164) the furnaces are represented by shallow pits, with an internal diameter of 0.3m lined with clay, which on the inner face are burnt and vitrified.

In north European examples of the slag pit furnace, the molten slag was encouraged to flow into a pit beneath the main body of the shaft (Figure 5.1.2). Once smelting was completed, a fresh pit was dug and the shaft rebuilt over it (Abrahamsen *et al*. 1998). Rare British examples occur in Essex and Norfolk (Tylecote 1990, 136). Slag pits are commonly found in the low land areas skirting the Baltic Sea (Smelkalova *et al*. 1993) and elsewhere in central Europe, for example Poland and Bohemia (Pleiner 2000, 149 - 163). Once the spongy mass of iron and slag, the bloom, was formed it was removed either through an opening in the side or the top of the furnace. The repeated heating and hammering of the bloom removed slag and iron, as slag and iron rich hammerscale, leaving a malleable lump of iron that could be forged into an artifact.

Shaft furnace technology was a batch process. Once an iron bloom was formed, the process would be interrupted to remove the bloom. The formation and removal of the bloom frequently resulted in erosion of the lining, and cracking of the furnace walls, as the furnace cooled (Personal observations on an experimental furnace at Rievaulx Abbey, North Yorkshire, 2002). The furnace would have to be relined, for example the excavated furnace at Kyloe Cow Beck, North Yorkshire (Vernon *et al*. 1999a, 22) or even rebuilt (Powell 1999). Once a furnace was beyond repair, it was either demolished and a new one constructed on its base, or it was left to the elements and a new furnace constructed close by. By the medieval period the slag was being removed via a tapping arch and channel. Excavations at Castleshaw, Greater Manchester (Redhead 1992 and 1993), and Myers Wood, West Yorkshire (Vernon *et al*. 2003; Clay *et al*. 2004, 21), provide such examples.

A common element to all smelting sites is a slag dump usually close to, and frequently down slope, of the furnace. Ore was probably crushed and washed close to its source, thereby reducing the amount of gangue or waste material being transported. Ore preparation areas have been noted at Stanley Grange, Derbyshire (Challis 2002). Ore roasting areas can also be identified, for example at Minepit Wood, Sussex (Money 1974) and Myers Wood, West Yorkshire (Vernon *et al*. 2003). Usually the roasted iron ore is found as small-disseminated fragments, together with charcoal fuel. The former can indicate where the ore was roasted, prepared or stored, whilst the latter tends to be a valuable commodity and rarely found (Crew 1995). Roasted ore may also be found encapsulated in the slag, for example at Myers Wood (Clay *et al*. 2004, 27). Until recently, evidence was scant for charcoal production on iron smelting sites, but examples have now been found in common association with bloomery operations in Upper Teesdale, County

Durham (Gledhill 1999, 8), Eskdale, Cumbria (Leigh 1999) and Myers Wood, West Yorkshire (Vernon *et al*. 2003; Clay *et al*. 2004, 15).

Mechanization of iron production probably occurred in the 13th and 14th centuries, for example at Bordsley Abbey, West Midlands (Astill 1993). Reference to an "Oliver" in the Calder Valley in 1349/50 may refer to a treadle hammer operated by applying force to a lever (Jewel *et al*. 1981) or more likely a hammer driven by waterpower (Tylecote 1990, 142). The introduction of waterpower on iron-working sites mechanized the operating of bellows and hammers and eventually bloom-smithies incorporating this technology were replaced by the charcoal fired blast furnace.

The proto-blast furnace (or high bloomery) could produce a cast iron. Examples from Continental Europe, where it was known as the Stückofen, show that it was a taller structure (Figure 5.1.3). Tylecote (1990, 213) comments that furnaces higher than 2.0m would allow the ore to remain in contact with the burning charcoal and the reducing carbon monoxide for longer periods. Some of the iron oxides would convert to iron carbide (Fe_3C) and cast iron would be produced.

The *Indirect Process* utilizes a blast furnace to produce a brittle cast iron that has to undergo further treatment at a finery and chafery - the former to produce a wrought iron and the latter to remove slag and create a marketable product (Tylecote 1990, 213 - 222). Blast furnace technology was a continuous process, and a smelting campaign conducted three or four times a year was normal by the 1600s (Schubert 1957, 243). Between 23rd October 1592 and 23rd April 1593 the Rievaulx blast furnace produced c192 tons in a single campaign (Schubert 1957, 401 - Appendix 10). The fundamental requirements of a blast furnace operation are summarised in Figure 5.1.4. Early blast furnaces were fueled by charcoal and the bellows were water-powered. An extensive woodland for charcoal production combined with a reliable supply of water generally governed the furnace's location. Iron ore stores were located close to the blast furnace, for example at Duddon, Cumbria (Dunn 1998). At Rievaulx, North Yorkshire, there are deposits of roasted ore (*personal observation*) immediately to the northwest of the probable site of the furnace. Charcoal stores were usually sited furthest away from the furnace (e.g.Duddon, Cumbria), to reduce the risk of charcoal ignitions, and were often the largest building on the site. The shaft of the blast furnace was elevated off the ground away from surface water. Around the base of the furnace were two openings, usually on two adjacent sides, one for introducing the blast of air, the second for tapping the iron and slag. The air blast was produced by bellows operated by a water wheel, whilst the casting floor lay in front of the tapping arch.

Unlike the bloomery process which produced iron rich slags (50% to 60% iron oxide), the blast furnace was very efficient. On average, blast furnace slag contains less than 5% iron oxide (Vernon *et al*. 1998a).

Slag residues are probably the most prominent features of an iron-smelting site. McDonnell (1983; 1986) has catalogued nine types of iron-working residues and these are detailed in Appendix 2. In the *Direct Process* the iron ore is gradually reduced as it passes down through the furnace and eventually iron particles are formed that are encapsulated by slag. These particles eventually begin to melt and form an iron bloom just above or below the tuyere, attached to the furnace wall. The less viscous slag descends to the lower part of the furnace, although a high proportion remains mixed with the bloom. Very rich iron ores are exceptional and would only produce small amounts of slag. The slag derived from impure ores containing for example, quartz (SiO_2), and other minerals, will have to be tapped and allowed to flow from the base of the furnace. At no time during the process does the iron become liquid. The iron rich slag from bloom-smithing was often re-smelted (i.e. Crew 1995; McDonnell 1995c).

Where the slag is tapped in the bloomery process, it is allowed to flow out of the furnace tapping-arch into the tapping channel. Such slag tends to be grey to black, sometimes with a metallic lustre. The upper surface exhibits ropey flow features whilst the lower surface is often irregular and encrusted with material from the base of the tapping channel.

Bloomery slag consists mainly of fayalite ($2FeO.SiO_2$) with up to 25% other oxides including wüstite (FeO), and glassy phases (McDonnell 1988, 28; Tylecote 1990, 129 -130; Powell *et al*. 2002). Bloomery slag may also contain variable amounts of magnesium, aluminium, silicon and calcium and form, for example, hercynite or fosterite (Powell *et al*. 2002). The iron content of bloomery slags is also variable. Tylecote (1990, 186 - Table 91) showed that the slag composition of analyzed samples from the early medieval period had an iron oxide content frequently between 40% and 70%.

In contrast, charcoal-fired blast furnace slag is generally glassy with an iron oxide content of less than 5% although higher values do occur. Iron prills may also be present (Tylecote 1990, 217 - 218 and Table 106). The green, blue or even black colouration is produced by residual iron (Tylecote 1990, 221). It was not unknown for bloomery slag to be re-smelted in the blast furnace, as it could have higher iron content than the local iron ore (Tylecote 1990, 216).

5.1.2 Shaft type furnaces

The term 'shaft furnace' has been used in the broadest sense to include any furnace constructed as a vertical cylindrical shaft and includes both non-tapping and tapping types. Tylecote (1990, 124 - 201) provides ample British examples of excavated shaft furnaces. Many are from the Weald and Northamptonshire that smelted ironstone from Cretaceous and Jurassic strata, respectively. Other examples tend to be from wider areas. The sideritic ironstones of the Carboniferous Coal Measures have supported significant iron producing industries, but they are relatively unrecorded. In West and South Yorkshire for example, only two bloomery sites has been excavated at Rockley Smithies (Crossley and Ashurst 1968) and Myers Wood (Vernon *et al*. 2003; Godfrey *et al*. 2003; Clay *et al*. 2004).

There are three main factors that seem to govern the location of a bloomery: a supply of water and sources of iron ore and fuel. Cowper (1898, 100) recognised that many Cumbrian bloomery furnaces were located next to running water, although none were water-powered. The majority of similar sites in the North Yorkshire Moors National Park and those in West and South Yorkshire tend to confirm this aspect. Water is used for the manufacture of clay furnace lining and may be required for quenching iron blooms, as recent experiments at Rievaulx Abbey have demonstrated (Bradford University, Ancient Metallurgy Research Group, June 2002 and July 2003). Shaft furnace sites would require local resources. Place names, for example 'Cinder Hill' or 'Black Intake', can often indicate the location of a bloomery site. Charcoal would also be required as a fuel. Coppiced woodland, used for charcoal production, is often referred to as 'Hagg' (Smith 1956, 256; Proudman 1987; Gledhill 1992) Similarly 'Eller' or 'Birk', Old English for Alder and Birch, respectively, may also indicate the tree species used for charcoal production (Smith 1956, 36 and 150).

Whilst the furnace, slag dump, charcoal storage and ore store or ore roasting areas are the main components of most bloomery sites, excavations of such sites rarely give the complete picture as they tend to concentrate on the furnace and slag dump.

5.1.2.1 Excavated examples.

The following examples of excavated British iron-working sites identify the main features associated with shaft furnace operations.

5.1.2.1.1 Minepit Wood

Minepit Wood, Sussex (Money 1974) is one of the few examples where furnaces, ore and charcoal stores were found in close proximity and adjacent to a pit where the siderite ore was mined. Most of the excavated features are believed to date from the 14th and 15th century (radiocarbon 14 date). The incomplete remains of the smelting furnace consisted of an outer stonewall with an internal layer of clay which also formed the furnace bottom (Figure 5.1.5). It was roughly horseshoe shaped with an overall diameter of approximately 1.8m. Adjacent to the furnace was a dump of clay that Money (1974) suggests was used for furnace lining. Post-holes suggest that a timber hood or shelter had been built over the furnace. The furnace area around the tuyere, which consisted of a piece of tap slag with a hole through it, was heavily vitrified. The slag from the operation was tipped over a wide area, but the excavation did not determine the full extent of the tip.

The ore-roasting furnace was a three-sided masonry structure with its back bedded into natural clay (Figure 5.1.6). Internally, the structure was about 2.4m square narrowing to 1.6m at its mouth. The charge consisted of a mixture of well-calcined ironstone nodules and charcoal. Evidence from postholes and wall foundations suggested that much of the structure was roofed. Spreads of charcoal along the positions of walls indicate sub-divisions within the structure for storing ore and charcoal. Figure 5.1.7 is the published reconstruction of the Minepit Wood site together with the excavation details (Money 1974).

5.1.2.1.2 Northamptonshire examples

The Northamptonshire ironstone has supported an economically significant iron industry since the Iron Age; only in the latter half of the last century did mining cease. The database produced by Bellamy *et al*. (2001) contains 213 iron-working sites in northeast Northamptonshire. Three of those sites have been excavated and well documented, and will be cited as examples.

(i) Wakeley

Jackson and Ambrose (1978) describe excavations of an Iron Age / Romano-British site. Seven furnace sites were located and they concluded that the furnace types could be subdivided into three groups. ‘Type 1 furnaces’ (‘bowl’) were flat bottomed and usually built on, or in the bedrock, possibly 0.2 - 0.3m below surface level. Furnace diameters ranged from 0.6m to an estimated 1.3m. The wall thickness varied from 0.02 - 0.10m. Fused slag was usually found at the base of the furnace. There was usually a ‘raking pit’ in front of the tapping arch position. ‘Type 2 furnaces’ (‘sunken-shaft’) were constructed in specially dug pits ranging in depth from 0.4 to 0.7m. The top of the tap arch was usually 0.3m above the base. Furnace diameters varied from 0.3m to 0.7m. There was usually evidence for multiple relining. In two examples, the front of the furnace had been completely rebuilt and overlapped the furnace sides. ‘Type 3 furnaces’ (surface shaft) were usually in a poor state of preservation. One example (Figure 5.1.8) had been repaired on two occasions thereby reducing the internal diameter to 0.3m. In front of the tapping arch position was a slag-tapping channel 1.8m long and with an average width of 0.6m, with a small quantity of flow slag still *in situ*.

(ii) **Laxton**

At Laxton, Jackson and Tylecote (1988) take the Wakeley furnace classification further by suggesting that ‘type 1’ preceded the ‘type 2’ furnaces. Five large furnaces of Romano-British age were recessed into a slope, at individual depths of 0.3 and 0.8m. All the furnaces had internal diameters of between c.1.3 and 1.4m. The furnace walls had a thick layer of slag fused to their internal surfaces and were, including the re-lining, up to 0.3m thick. The existence of furnace lining in the slope behind the furnaces indicated they had been re-used many times. It was noted that the top of the furnace walls were overhanging the furnace interior, hence producing a bowl shaped appearance. However it was speculated that this may be due to re-lining and that the original furnace was vertical. Slag pits were cut into the bedrock down slope of the furnace. The width of the furnaces and slag pits varied between 2.7 and 3.3m and were about 5m long. Excavated examples of the Laxton furnaces are shown in Figure 5.1.9. A working area for the preparation of ore was located up-slope of the furnace.

Six examples of 'sunken shaft' furnaces were also found and excavated. Internal diameters varied from 0.4 to 0.5m and the wall thickness from 0.15 to 0.20m. One furnace provided evidence for the tap arch 0.4m up from the furnace bottom. Two of the furnaces were built across an earlier furnace.

During 1998, another large furnace was excavated at Laxton (Crew 1998). The furnace exhibited four phases of construction. The original phase had stone casing and three zones of red oxidized clay on different alignments identified in the later phases. The final phase was 1.5m in diameter at the base. It is speculated that the furnace may have had up to five air inlets.

Bellamy *et al*. (2001) have concluded that the large furnaces discovered at Laxton constitute a fourth type of furnace. They are similar to a 'type 3' (surface shaft) but both the base of the shaft and the slag tapping area are set in a specially dug pit and draw parallels with similar types in France, Germany and Austria.

(iii) **Cendry Holme**

Bellamy *et al*. (2001) published a 1.0m resolution magnetometer (Philpot Electronics' Differential Fluxgate) survey of an iron-smelting site at Cendry Holme. The survey identified an area approximately 40m by 40m with numerous positive anomalies. The published values range between -77nT to 66nT. Several anomalies were interpreted. One area with clustered positive data was thought to be an ore roasting area. Excavation of this anomaly produced a layer (0.15m thick) of red soil impregnated with iron fines and slag at a depth of 0.2m. It was concluded that this was probably the residue from a roasting hearth or an area for preparing the roasted ore. Most other anomalies were related to slag. One furnace was partly exposed on the surface and coincided with a positive anomaly. The furnace was covered by 0.45m of topsoil. Only the lower 0.25m survived and consisted of a circular bowl, 0.3m in diameter. The internal surface was coated in a 0.075m layer of slag. A slag-tapping aperture was 0.1m wide with a single run of tap slag *in situ*. The furnace had been built into an earlier rectangular clay and stone lined pit at least 0.50m wide and 1.35m wide. The results of the geophysical survey and the excavation are shown in Figure 3.4 (Bellamy *et al*. 2001)

5.1.2.1.3 Crawcwellt West and Bryn-y-Castell, Snowdonia

Crew (1989) excavated the Crawcwellt West Iron Age site in 1986 – 89. It is an upland settlement with a prominent sub-circular platform with an internal width of about 6.5m wide that housed 10 furnaces (See Figure 5.1.10). The furnace remains frequently overlapped. The last two furnaces (F04 and F41 on Figure 5.1.10) were well preserved. They were clay-lined "bowls" constructed in the sub-soil with internal diameters between 0.25 and 0.30m. The walls were between 0.25 and 0.30m thick with a 0.15m break representing the position of the tap arch. The tuyere position was represented by a 3.5 cm hole at ground level and at 90º to the arch. All the furnaces were aligned in the same direction with the tap arch facing the entrance to the platform. Several lumps of bog iron ore were also discovered. Experimental work by Crew (1989) suggests that each furnace could last with repairs for 20 smelts and could have produced 20 raw blooms weighing 2 kg each. Crew (1989) has also recorded over 450 stake holes associated with other structures on the site. Some are aligned around the arc of the platform whilst most are concentrated in the vicinity of the furnaces. Several dumps of bog iron ore were also recorded.

At Bryn-y-Castell late Iron Age hillfort, Crew (1984) reports on one furnace with an internal diameter of 0.25m. The heavily vitrified lining exhibited at least two phases of use. Adjacent to the tapping arch gap, there was a small platform of unbaked clay that was interpreted as the site of the bellows or a small working platform.

5.1.2.1.4 Scottish Examples (Scottish Highlands)

Photos-Jones *et al*. (1998) records several furnaces with stone lined exteriors. Tamheich Burn consisted of flat stone slabs that varied in size from 0.2 - 0.3m by 0.1 - 0.2m that were arranged into a small mound with a flat area of stone slabs on top. When the first layer of stonework was removed the outline of a centrally built clay-lined furnace was revealed (Figure 5.1.11(a)).

At the Allt na Ceardaich site, as well as the stone slab arrangement described above, a large upright slab was used to delineate the structure. The furnace bowl was roughly square in plan (Figure 5.1.11(b)).

A survey of undated sites on Rannoch Moor (Aitken 1970) also suggested that most furnaces were enclosed in a ‘box’ of stone about 30cm high, constructed over a hollowed out bowl. The ‘box’ interior was lined with clay. It was suggested that the stone structures were partly demolished to remove the bloom. This may account for the lack of well-preserved furnaces in the Scottish Highlands. Aitkin (1970) states that most of the sites on Rannoch Moor were, *'in easy reach of bog iron ore, trees and generally a stream'*.

5.1.2.1.5 Kyloe Cow Beck, North Yorkshire

The Department of Archaeological Sciences, University of Bradford excavated this medieval site in 1997, and revealed one furnace (Vernon *et al*. 1999a; Powell *et al*. 2002). The external diameter of the furnace structure including burnt clay varied between 1.8m and 1.4m. The actual shaft was c0.4m in diameter with a 0.15m thick lining. The latter was constructed from local clay with the addition of shale. A 1.0m long and 0.25m wide tapping channel was identified at a depth of between 0.4 - 0.5m leading away from an intact tapping arch towards a slag dump. Figure 5.1.12 shows a general excavation plan of the furnace. The source of ore was probably from the Jurassic 'Dogger' ironstone horizon.

5.1.2.1.6 Discussion on excavated shaft furnaces

The examples cited above demonstrate that shaft furnaces can be freestanding (with or without walling), built into a bank, or constructed in an excavated hollow. It is unclear whether the specific location or construction can be regarded as a phase in their technological evolution, as examples illustrating all forms of construction can be found from the Iron Age (e.g Crawcwellt West and Bryn-y-Castell, Snowdonia) through to the Medieval period (e.g. Kyloe Cow Beck). It is possible that construction into a bank reduces the heat loss. Furnaces are generally located next to water although this does not seem to be always an essential requirement. The Bryn-y-Castell furnaces, for example, are on top of a small hill that offered a defensive function. A fundamental requirement would be a local source of ore, and all the examples have been linked to a specific source of ore. Charcoal fuel would also have been a major consideration. Certainly, as the demand for iron production grew it would become more organised and production would be fixed in specific centres.

Some researchers (Jackson and Ambrose 1978; Jackson and Tylecote, 1988; Bellamy *et al.* 2001) have tried to introduce and later modify a furnace typology for the Northamptonshire / Rutland area. However, variability may simply arise because of the type of ore supply, the operating experience, charcoal availability, amount of iron required, or manpower availability etc. It has been estimated that the large furnace at Laxton (Crew 1998) would have required a charge of 200kg to fill the basal part of the furnace. Total amounts of 500kg ore and 600kg of charcoal may have produced five blooms each weighing 20kg. The five tuyeres would require at least five men to operate the bellows. At Laxton the iron ore may have even been blended with a fluxing agent to produce a self-fluxing ore (Crew 1998).

Tylecote (1990, 133) concludes that there is no evidence to support complex furnace typologies and comments that *"the major drawback encountered by all is the paucity of the archaeological record"*. Tylecote (1990, 157) has described the Ashwicken iron-working site, Norfolk as being an example *par excellence.* It is Roman and contains the remains of up to seven furnaces. It is exceptional as one of the furnaces was preserved as a perfect vertical shaft, 1.4m high and probably the tallest shaft furnace remains found in Britain. Tylecote (1990, 133) could also have added to his conclusion above that the majority of excavated furnaces are poorly preserved.

Archaeological geophysical surveys may identify the key features on an iron-smelting site without the need for excavation, especially if the benefits from the excavation are minimal, both in terms of finance and knowledge. Geophysical surveys can locate a furnace and enable the furnace diameter to be estimated, and even its state of preservation, as examples in the following sections will demonstrate.

5.1.2.2 Geophysically surveyed examples

The following examples of geophysically surveyed shaft furnace sites have been sub-divided based on site complexity and do not correspond to those previously cited for excavated furnaces. The examples are mainly located in North Yorkshire, and to a lesser extent Northamptonshire. They demonstrate how geophysical surveys can provide information on furnace morphology.

5.1.2.2.1 Sites with one identified shaft furnace

a) Ewecote, Bilsdale, North Yorkshire

Ground conditions: Pasture.

Research by the Department of Archaeological Sciences, University of Bradford, has identified iron-working sites that could have associations with adjacent monastic quarries at Ewecote and Wethercote, Bilsdale, North Yorkshire. The quarries have been recognised as the source of the building stones for Rievaulx Abbey (Fox-Strangways 1892, 188; Weatherill 1954; Fergusson and Harrison, 1999). The geophysical surveys were conducted over relatively flat areas to the east of the quarries to provide information on any ancillary activity associated with the quarrying, for example the forging of quarrying tools (Vernon 2000c). The locations of the surveys are shown in Figure 5.1.13.

Only one of the surveys, Ewecote, identified industrial activity. The 1.0m resolution fluxgate gradiometer reconnaissance survey identified three distinct positive anomalies that suggested industrial activity on, (i) the western edge of the survey associated with a spread of slag, (ii) centrally, and (iii) at the northern end of the area, adjacent to a stream bank (Figure 5.1.14). The latter anomaly (iii) was interpreted as a possible single furnace and consisted of a cluster of positive data. The highest recorded value is 903nT in a geophysically 'noisy' area. A possible rectangular anomaly enclosed the furnace. A 0.50m resolution survey (Figure 5.1.15 (a to c)) provided little additional detail. A 0.25m resolution survey (Figure 5.1.16 (a to d)) established that a substantial linear anomaly, about 3m long and probably a tapping channel, ran southeast from the furnace. There was also a grouping of high positive values (highest 1073nT) around the southwest quadrant of the furnace. Exploratory removal of the topsoil identified slag, burnt stones and ash. Figure 5.1.17 shows the positive furnace anomaly in three dimensions. Two ridges on the east and west sides of the anomaly are unusual and have not been noted on either experimental or actual surveys before. They may represent furnace walling and may be an indication of the furnace's state of preservation. The raw data for the anomaly is shown in Figure 5.1.18. The high positive data in the tapping channel probably indicate the presence of *in situ* slag. Figure 5.1.19 shows north-south and east-west profiles of the fluxgate gradiometer data through the furnace. The north-south profile shows a negative trough on both the north and south sides of the furnace, whilst the east-west peaks correspond to the possible sides of the furnace. These results are difficult to interpret. They may suggest that the furnace walls are far enough apart to produce two separate peaks on two sides of the furnace, with little in the way of magnetically strong material in the fill that could contribute to the response.

Immediately to the south of the furnace a linear area of slightly higher values (-10 to 10nT) to the background (range -4 to 4nT) trends northwest / southeast. At its eastern end the anomaly disperses and may represent a previous boundary feature that has been ploughed out.

An earth resistance survey was confined to the northern end of the field. The data provided little additional information. Two areas of higher earth resistance data straddle the linear anomaly and may represent either a tip from normal field clearance operations or the local geology lying close to the surface (Figure 5.1.20).

b) Hagg End, Bilsdale, North Yorkshire

Ground conditions: Wooded.

The site, occupied by a prominent slag tip, was found during field walking in 2000. It is located in partially wooded rough grazing land immediately west of the River Seph, Bilsdale. A hollow may represent attempts to mine the Main Seam ironstone band. At the southern end of the site there is a partially buried wall and a possible overgrown excavation overlooking the River Seph. The tips show signs of excavation (Vernon 2000c).

The initial fluxgate gradiometer survey was conducted at 0.50m resolution. (Figure 5.1.21 (a to h)) The slag-tip at the northern end of the site produced positive values between 100 and 200nT that formed a sub-circular anomaly about 8.0 to 10.0m in diameter. On the southwest side of the tip, a linear tongue of positive values extended in a southwesterly direction and terminated at a cluster of high positive data (609nT) interpreted as a furnace, and confirmed in the 2003 excavations. A further tongue of high positive values (less than 100nT) extends south from the cluster. The general area south of this anomaly contained several distinct bands of positive (generally between 20 to 40nT) and negative data. Some of the banding is linear. To the south, data values reduced to less than 10nT. Stonework noted on the surface may extend north-north-east through the eastern part of the survey and may form a boundary to the higher positive values. The interpretation of the survey is shown in Figure 5.1.22.

A 0.25 m resolution survey over the furnace anomaly is shown in Figure 5.1.23 (a to g). Figure 5.1.24 shows the data values for the anomaly. The anomaly is roughly circular and generated a maximum positive value of 765nT. On the surface this feature is set into a small embankment. The tongue of positive data extending to the northeast may suggest that the tapping arch was on the east side of the furnace, in a hollow. The weaker positive data on the south side of this anomaly generates much lower values and is probably slag.

Although there is only one identified furnace at the Hagg End site, the surface and geophysical evidence would suggest the site was the location for several other activities. The hollow or pit may well have been used for mining ironstone and a source of clay. If the ore was mined *in situ* then it would have been roasted prior to smelting. The area between the furnace and the pit, with the banded positive data might have been the location for this activity. The furnace was successfully proved by excavation in July 2003 and found to have an internal diameter of about 0.5m with evidence of relining.

5.1.2.2.2 Sites with more than one identified shaft furnace

a) Kyloe Cow Beck, Bilsdale, North Yorkshire

Ground conditions: Pasture.

The Kyloe Cow Beck site was discovered in 1996 by field walking. The site is located in Smiddale ('valley of the smiths' in Scandinavian) on the east side of Bilsdale. The site also lies near to the outcrop of the Dogger ironstone to the east at the top of Smiddale. The Main seam ironstone was mined in Crossett Plantation to the west. The location of the survey is shown on Figure 5.1.25.

A 1.0m resolution fluxgate gradiometer reconnaissance survey revealed an extensive spread of slag. Two clusters of high positive data, with maximum values of 321nT and 469nT, were noted on the west and east sides of the slag spread, respectively. They were interpreted as furnaces (Vernon *et al*. 1999a, Powell *et al*. 2002).

The methodology, with respect to survey resolution, derived from the detailed Lock Farm experiment was applied to the Kyloe Cow Beck site. The area of slag was resurveyed at 0.5m resolution and the eastern furnace was also surveyed at 0.25m resolution. The latter survey produced a higher response (869nT) than the 1.0m resolution survey. The positions of the survey grids, together with data plots and the data values for the eastern furnace, are shown in Figure 5.1.26.

During 1997, the eastern furnace was excavated and its position corresponded to the large positive anomaly identified on all three surveys. The external dimensions of the furnace were 1.8m and 1.4m on the north-south and east-west axis, respectively. Powell *et al*. (2002) record that the internal diameter is c0.4m with a lining 0.15m thick that showed signs of renewal and vitrification. The furnace was also surrounded by a 0.5m thick halo of heat-affected clay. Adjacent areas of lower magnetometer readings correlated with thin (<0.5m) spreads of slag.

Similar to Lock Farm (Chapter 4.3), the Kyloe Cow Beck data revealed a slight bulge on the northwest side of the positive data that corresponded to the excavated tapping channel. The grouping of high positive values on the north side of the furnace coincides with the location of the tuyere. Reference to Figure 5.1.1 indicates that the highest temperatures occur around the tuyere and as the bloom forms in this area it is a possibility that slag containing iron oxides might have remained attached to the furnace lining. This area inside the furnace will also be prone to slag attack and so successive removal and reconstruction of the furnace lining will inevitably lead to a build up of iron rich material. In the case of Kyloe Cow Beck, excavation has shown that the furnace was relined at least five times in the tuyere area (Vernon *et al*. 1999a).

Photographs in Figure 5.1.27 show the furnace during excavation with some of the main features located. Figure 5.1.28 compares the 0.25m survey data of the eastern furnace before and after the excavation together with the excavation results. The furnace fill and the slag tip to the west of the furnace were removed during excavation. Some samples from the top of the furnace were taken for archaeomagnetic dating but overall the furnace was kept intact. After recording, the furnace was backfilled with soil and the ground was re-turfed to its original level. The differences between the pre- and post-excavation magnetic responses on Figure 5.1.29 suggest that the removal of fill material, and some of the furnace lining for dating, reduced the magnetic response from the furnace anomaly. Both before and after excavation surveys were conducted with a fluxgate gradiometer held at the same height above ground level. The 0.25m resolution data from the unexcavated west furnace is shown in Figure 5.1.30 The data suggests that the furnace is also intact and the tapping channel runs from the furnace in a southwest direction, the down-slope side.

b) Ridlington, Oakham, Rutland

Ground conditions: Arable land, field under stubble.

The Ridlington site was discovered by field walking (J. Cowgill, *pers. comm.*). It lies about 8 kilometres south-south-west of Oakham in the County of Rutland close to or on the outcrop of the Jurassic Northhampton Ironstone (Whitehead *et al*. 1952, Plate VI). Iron smelting sites of Romano-British age have been excavated about 10km to the east at Wakerley (Jackson and Ambrose 1978) and Laxton (Jackson and Tylecote 1988; Crew 1998). When the fluxgate gradiometer survey was conducted the field was under stubble, covered by chaff and straw. It is bordered on the south-east side by a grass track and a hedge. All other sides are open. The land falls away to the south-west. Figure 5.1.31 shows the grid layout and the main surface features together with the data (Vernon, 1999).

There are several major anomalies on the 1.0m resolution geophysical data (Figure 5.1.32 (a to l)). One, towards the northwest corner, consisted of two parallel singular readings of 54nT and 128nT. The association with a linear anomaly, probably a ditch, suggests they may be generated by iron objects within it. Two prominent anomalies produced maximum values of 140nT and 253nT and are positioned close to a crescent shaped anomaly with positive values ranging between 14nT and 72nT**.** These features are interpreted as two furnaces and a slag tip. Below a clipped range of -20nT to 20nT several linear anomalies become well defined. The full interpretation is shown in Figure 5.1.33.

A 0.5m resolution fluxgate gradiometer survey was conducted over the main anomalies. Figure 5.1.34 shows the spread of values associated with the western furnace (?) anomaly. Untypically for furnaces elsewhere (Ewecotes and Kyloe Cow Beck, see above), the positive values do not form a tight sub-circular grouping but rather are spread laterally in a direction parallel with the adjacent track. Field evidence in the form of crop sowing and spraying tracks, and hence the direction of original ploughing, indicate that the lateral spreads of positive data coincide with the direction of ploughing. It is suspected this is an indicator that the furnace has been damaged by ploughing. Fragments of furnace lining embedded in the top soil gave confirmation that furnace had been damaged by ploughing (J. Cowgill, *pers. comm.*).

The 0.5m resolution fluxgate gradiometer survey results are shown in Figure 5.1.35 (a to h), and confirmed that the east furnace (maximum value 359nT) had a clear negative halo surrounding it. The west furnace (maximum value 257nT) was more diffuse. There were several weakly contrasting features between the two furnaces, but it is not known what they may represent. Another area of positive data trends northwards from the eastern furnace. Features like this on other surveys often represent the location of tapping channels (e.g. Ewecotes). However, in this instance this feature is on the uphill side of the anomaly and the opposite side to the slag dump, and may represent furnace collapse material.

5.1.2.2.3 Complex Shaft Furnace Sites

Shaft furnaces can be found related to other activities or form part of a complex site as the following three examples demonstrate.

a) West Hawk Farm, Ashford, Kent

Ground conditions: Excavated surface.

A 1.0m fluxgate gradiometer survey by Geophysical Surveys of Bradford (Paul Booth, Oxford Archaeology Unit, *pers. comm.*), revealed a major Romano-British Settlement, centred on Westhawk Farm. Subsequent stripping of top-soil prior to detailed recording by the Oxford Archaeological Unit revealed revealed a row of furnace bases and smithing debris associated with a positive anomaly (Vernon 1999).

Two fluxgate gradiometer surveys, at 0.5m and 0.25m resolution, were conducted over the furnaces and smithing debris. The relationship of the two surveys are shown in Figure 5.1.36. The results of the 0.5m resolution survey are shown in Figure 5.1.37. Between -100nT and 100nT it is possible to identify a rectangular anomaly surrounded by high positive data. A further linear anomaly runs from the southern end of the rectangle in a westerly direction. A pseudo-rectangular anomaly occurs in the northeast corner of the survey. At -40nT to 40nT the central rectangular anomaly is well defined but the negative data mask other anomalies.The eastern side of the anomaly produces a positive response greater, both in magnitude and extent, than that produced by the western edge. At ranges below -30nT to 30nT a further linear anomaly is identified trending roughly north-south. The individual furnaces cannot be identified on the 1.0m or 0.5m resolution surveys. All the anomalies are identified on Figure 5.1.38.

The area over the rectangular anomaly (Figure 5.1.38, B1-3) was resurveyed at 0.25m resolution to try and differentiate between individual furnaces. The 0.25m resolution fluxgate gradiometer survey is shown on Figure 5.1.39. The rectangular anomaly can be identified between -400nT to 400nT. The central positive anomaly, now with a well defined area of negative data, produced a response above 2000nT. The positions of furnaces can also be identified as a row of small positive anomalies. The interpretation, and the data values from the 0.25m resolution survey from the furnaces, are shown in Figure 5.1.40 and 5.1.41, respectively.

Figure 5.1.42 combines the anomalies identified on Figure 5.1.38 and 5.1.40. The advantages of the higher resolution survey are apparent. The 0.25m resolution surveys do produce a regular distribution pattern of positive data in the area where the furnaces are located. The scale of readings would also suggest that the furnaces are small (<0.5m) and the positive data spread may suggest that succesive furnaces may have been partially built on the earlier furnace, perhaps to economise on space utilisation. The values associated with the furnaces are lower than normally encountered and the surface evidence (*personal observation*) suggests that only the bases of the furnaces remain. It is suspected that the response is predominently produced from the basal burnt clay of the furnace as there is no heavily vitrified clay present that usually represents the furnace lining.

Comparison of the two surveys (Figure 5.1.42) shows that it is possible to refine the dimensions of linear anomalies. In addition several anomalies that might represent postholes were noted. The regularly spaced clusters of positive data that represent the post holes are probably partially backfilled with slag. The lack of slag accumulations in the vicinity of the iron-working would suggest that it has been removed, possibly for filling foundation ditches. Figure 5.1.43 shows the data from the excavation report for comparison.

b) Myers Wood, Huddersfield, West Yorkshire

Ground conditions: Heavily wooded sloping ground.

This site contains prominent slag dumps in a thinly wooded area adjacent to a stream. It lies close to the conjectured outcrop of the Black Bed Ironstone, Lower Coal Measures. A monastic grange was located 1 km to the south and it is speculated that the iron-working dates from this period. Excavations were carried out on five furnaces during 2002 and 2003 (Vernon 2001b; Vernon *et al*. 2003; Godfrey *et al*. 2003; Clay *et al*. 2004) and pottery confirmed that the site was operating between the late 13th and early 15th centuries (Cumberpatch, 2002). A topographical survey of the site identified six slag tips and a charcoal production platform (Figure 5.1.44).

A 1.0m resolution reconnaissance fluxgate gradiometer survey confirmed the approximate limits of the ironworking activity (Figure 5.1.45). At a clipped range of -500nT to 500nT (Figure 5.1.46 (a to l)) two areas were identified that contain high positive values. One was roughly rectangular and occupied much of the southern half of the survey. The second area, located at the northern end, was irregular. At -200nT to 200nT two roughly circular anomalies identified by clusters of positive data were discernible that generated maximum values of 435nT and 413nT respectively. At lower clipping ranges, for example -65nT to 65nT (Figure 5.1.46 (h)), it is apparent that much higher positive data was concentrated within the southern rectangular anomaly. At lower ranges, for example -15nT to 15nT (Figure 5.1.46 (l)), the high positive data and associated negative values dominated the data. Only the areas immediately west and south of the rectangular anomaly are unaffected, where values less than 10nT are typical.

If a high pass filter is applied to the data it is possible to remove much of this 'high value noise'. Figure 5.1.47 compares filtered and un-filtered data and illustrates the data down to a clipping range of -5nT to 5nT. Many of the linear anomalies previously identified on the un-filtered data become sharper, and anomalies 1 and 2 are prominent.

The two positive anomalies 1 and 2 were resurveyed at 0.25m resolution. Figure 5.1.48 shows the data clipped to various ranges. The interpretation based on the 0.25m and 1.0m resolution reconnaissance surveys is shown in Figure 5.1.49.

A surface inspection around anomaly 1 yielded burnt stone, fragments of burnt ore, charcoal and a possible piece of furnace lining. The geophysical survey recorded values of 1300nT and showed the anomaly to be aligned approximately north-south. The highest values are concentrated on the northeast and east sides of the anomaly and may suggest the location of the tuyere. At lower clipping ranges there is a bulge of positive data extending in a northwest direction that might represent the tapping channel. The elongate appearance of this anomaly was originally thought to be due to furnace collapse material extending in a southerly direction. However when this anomaly was excavated a rectangular ore roasting hearth of stone construction was found, underlain by three furnace bases with tapping channels aligned roughly north-south. A piece of furnace lining, that had been subjected to slag attack, was *in situ* and was the major source of high positive data readings. Photographs of the excavation of anomaly 1 are shown in Figure 5.1.50 (a, b and c).

Anomaly 2 appeared to be covered by slag. The distribution of the positive data was unusual and roughly triangular in shape. There were two clusters of high values, 683nT and

666nT separated slightly by lower values (408nT) that might suggest the presence of two furnaces. An excavation of anomaly 2 revealed pockets of roasted iron ore that were responsible for the high readings. When the roasted ore was scanned directly with a fluxgate gradiometer they generated readings over 1000nT.

Figure 5.1.51 shows the data from all the reconnaissance surveys at 1.0m resolution with the main anomalies identified. A 0.5m resolution fluxgate gradiometer survey was conducted over the charcoal platform and the results from this survey are described in Chapter 5.1.3.2.1 on water-powered bloomery sites.

A fluxgate gradiometer (Figure 5.1.52) and magnetic susceptibility (Figure 5.1.53) survey at 0.25m resolution provided more detail on known anomalies and identified several others including another furnace, anomaly 3. This third furnace consisted of a cluster of positive data, 15m south of anomaly 1 and produced a maximum reading of 961nT. A linear tail of positive data (54 to 200nT), similar to the Ewecote furnace (Chapter 5.1.2.2.1 (a)), extended northwest from the cluster and can be identified in the data values shown in Figure 5.1.54. An excavation of anomaly 3 confirmed that the cluster was a furnace and the linear anomaly a tapping channel with the slag *in situ*. Photographs of anomaly 3 are shown in Figure 5.1.55.

The 0.25m resolution magnetic susceptibility survey responded to the spreads of iron slag and roasted ore. Figure 5.1.53 shows the results from the survey. One anomaly, an arc of four small clusters of positive data, was thought to represent the locations of four furnaces and was positioned close to a similar anomaly on the fluxgate gradiometer data. The anomaly would have to be shallow to be identified on the magnetic susceptibility survey. If they represented furnaces then the only remains would be the base or an area of burnt clay. To try to obtain clearer definition of the anomaly a 0.125m resolution fluxgate gradiometer survey was conducted. The survey showed the anomaly to consist of four distinct clusters of positive data, with values below 200nT, approximately 0.5m in diameter. Figures 5.1.56 and 5.1.57 show the 0.125m resolution the survey location, and the data, respectively. An excavation revealed concentrations of roasted iron ore and slag with roasted iron ore inclusions.

The value of the high-resolution surveys was also confirmed with the identification of parallel slag filled cart ruts on both the surveys (Figure 5.1.53 - photograph).

c) Weldon, Corby, Northamptonshire

Ground conditions: Excavated surface.

An archaeological excavation on a housing development at Weldon, on the east side of Corby, Northamptonshire found a Saxon iron smelting site and a series of east-west and north-south aligned stone walls thought to be part of a medieval complex (J. Cowgill, *pers. comm.*). In the central part of the excavation there was a spread of slag covering the floor of a possible room. A series of 1.0m square pits approximately 0.2m deep that had been excavated in a chessboard pattern bottomed the slag deposit. On the north side of the slag spread, and on the north side of an east-west aligned wall, a small furnace had been identified with an approximate internal diameter of 0.3m. It had been built into a c0.25m deep trench. Subsequent excavation identified a 1.5m long tapping channel. The remains of the furnace walls were barely 0.04m thick (Vernon 2001a).

Figure 5.1.58 shows the data from a 0.5m resolution fluxgate gradiometer survey fitted to the geography of the site. The clipped results from the survey are shown in Figure 5.1.59 (a to f). At a clipped range of -1000nT to 1000nT only four anomalies can be identified in a north-south alignment. They are evenly spaced and are produced by the buried remains of metal fence posts (J. Cowgill, *pers. comm.*). The known furnace generates a high value of 349nT and it is only represented by seven positive values. Between -500nT to 500nT the northern edge of the excavation is identified as an east-west linear anomaly of negative data and a cluster of linear anomalies also begin to appear in the southern part of the survey. At -100nT to 100nT, there is a weakly contrasting north-west/south-east trending linear anomaly to the northeast of the furnace. Further south of the furnace clusters of positive data are associated with slag dumps and roasted iron ore.

At ranges of -50nT to 50nT much of the area around the fence post anomalies and the furnace are masked by negative data. A series of closely spaced short linear anomalies to the southeast of the furnace were produced by the variable response from the chessboard series of 1m x 1m shallow trial pits.

Two 0.25m resolution grids were surveyed over the area of the furnace. The southern limit to the survey was an excavated wall, aligned approximately east-west. The results from this small survey are shown in Figure 5.1.60 together with the range of data obtained. At this higher resolution the highest value recorded on the survey was 478.7nT. The positive data forms an elongated cluster aligned northeast / southwest, approximately on the same alignment as the exposed portion of the furnace. The elongation in a southwest direction confirms the position of the tapping channel. The extension of the positive data back to the wall suggested that the wall was built later than the furnace. Other linear anomalies on the same orientation as the tapping channel were later confirmed to be a row of postholes (J. Cowgill, *pers. comm.*), almost certainly part of the structure that enclosed the furnace.

5.1.2.2.4 Sites without an identified shaft furnace

a) The Grange, Bilsdale, North Yorkshire

Ground conditions: Rough pasture.

This site differs from all the other examples; it is not a site solely for iron manufacture but is a component of a monastic grange. The iron-working at the Grange, Bilsdale was originally identified by the field name '*Cinder Hills'* and is thought to be on the site of a monastic grange (McDonnell 1972, 32; McDonnell 1985, 24). The site is a pasture that is divided by a straight east-west aligned wall. Several discrete hummocks, some composed of slag, break the natural lie of the land.

A 0.5m resolution fluxgate gradiometer survey between the east-west dividing wall and Ledge Beck revealed numerous linear anomalies and provided strong evidence for industrial activity. A large area of high positive data corresponded to a grassed hummock immediately on the north side of the dividing wall. South of the wall there are a number of unconnected high positive response areas that correspond to subtle undulations on the surface (Vernon 1995).

The Grange site was originally surveyed in 1995 (Vernon 1995). The original interpretation of the 0.5m resolution fluxgate gradiometer data is shown in Figure 5.1 61. The survey is characterized by a series of long linear anomalies trending north-west/south-east with shorter perpendicular linear anomalies. Two anomalies identified as slag dumps occur centrally (Figure 5.1.61, A) and to the east (Figure 5.1.61, B). The latter area is bow-shaped with linear anomalies interpreted as forming a small rectangular structure (Figure 5.1.61, G) on its northern limb. On the north side, there is a curved anomaly (Figure 5.1.61, H) that may be a boundary ditch and another linear anomaly (Figure 5.1.61, I) trends into the area from the northeast. The high gradiometer responses associated with it, suggest that it could be a slag-filled ditch. On the southeast side of the survey, two linear anomalies (Figure 5.1.61, J and K) run south-eastward and downhill towards Ledge Beck, and may represent channels for taking water from the site.

The four areas of the high positive values seem to be associated with linear anomalies. The largest (Figure 5.1.62, 6) is roughly rectangular, and has a distinct negative halo around it. These anomalies may represent iron-working areas or another industrial activity, requiring the use of a kiln or furnace, which on a grange site is quite possible. Elsewhere, anomaly 3 (Figure 5.1.62) and several smaller anomalies to the east of it, are positioned between linear anomalies, suggesting that whatever the anomalies are they may once have been confined to specific areas.

No furnaces were identified on the site from the original survey interpretation and it was considered that the furnaces were located to the north, in the vicinity of the Grange Cottages (See Figure 5.1.61). The presence of slag in the cottage gardens partly confirmed this idea (Douglas Ainsley, Grange Cottages, *pers.comm*.). A fluxgate gradiometer survey in the field on the east side of the cottages provided no further evidence for industrial activity. However, with the experience gained from surveying other bloomery sites the data was re-examined. Six very high positive anomalies were noted that could have been generated by furnaces. They have been identified on Figure 5.1.62, and they will require future investigation using a 0.25m resolution fluxgate gradiometer survey.

b) Fineshade, Northamptonshire

Ground conditions: Undulating rough pasture. Ex

The Fineshade Knoll lies to the northeast of Corby, Northamptonshire. The iron working area consists of a prominent knoll under rough grazing land that falls steeply on the eastern and northern flanks down to a stream. The Northampton Ironstone probably outcrops some distance to the west. It is unknown who worked the site. Roman iron-working sites are common in the area and the remains of Fineshade Abbey lie immediately to the north (Vernon 2001c; Bellamy *et al*. 2001).

The 1.0m resolution fluxgate gradiometer survey is shown on Figure 5.1.63, fitted to the geography of the site. Figure 5.1.64 shows the data clipped to various ranges. No furnaces were identified by this survey. Three specific areas produced clusters of high positive data.

(i) Adjacent to a gate on the northeastern corner of the survey. It consisted of a cluster of positive data (highest reading was 291nT) possibly surrounded by a pseudo-square area about 5m by 5m. There was also pronounced iron-spiking (475nT and 500nT) to the northwest of this anomaly.

(ii) In the southwest corner of the survey a cluster of positive data produced readings up to 437nT. There was also a cluster of iron-spikes immediately to the west of the anomaly, one had a very high value of 915nT and was almost certainly produced by iron.

(iii) In the central / southeast part of the survey there was a cluster of positive data with values up to 447nT.

At lower clipping ranges some of the iron-spikes formed linear anomalies that clustered in two distinct northeast / southwest trending bands. Below a clipping range of -50 to 50nT several weakly contrasting linear anomalies appeared to combine to form rectangles.

The interpretation is shown on Figure 5.1.65. Slag spreads are evident over much of the survey. However there are very few concentrations of slag that could be identified as definite slag tips. The survey indicates that there has been a significant amount of human activity in this area. However, it was not possible to correlate this activity precisely with the production of iron. There may, for example, be several phases of activity represented by the identified geophysical anomalies.

3.1.2.3 Discussion

Shaft furnaces may generate distinct anomalies that are usually identified as sub-circular clusters of positive data on fluxgate gradiometer surveys. Powell *et al*. (2002) have shown that the anomaly may represent multiple phases of furnace relining and surrounding burnt clay. Therefore, the size of the anomaly cannot be regarded as representing the true dimensions of the furnace associated with its last active phase, unless there is clear evidence from other sources, for example documentation or excavation.

A very shallowly buried furnace would produce a cluster of positive data approximately equal to the width of the furnace and the surrounding heat affected clay (Powell *et al*. 2002). The anomaly produced by the reburied Castleshaw furnace at Lock Farm (single phase of activity) was sub-circular, whilst that of the Kyloe Cow Beck (multi-phase) eastern furnace anomaly was slightly larger representing the increased size of the furnace produced by relining. There is no clear rule as to what represents the average furnace. The Laxton furnaces, for example, are very large in comparison to Kyloe Cow Beck and if they had ever been geophysically surveyed would probably have produced an irregular complex anomaly that was larger than normally encountered. The anomaly would possibly have consisted of several peaks representing the different phases of the furnace. However where a furnace that has been damaged by ploughing (e.g. Ridlington – Chapter 5.1.2.2.2 (b)) or where there is more than one furnace constructed on top of another one either directly or *en echelon* (e.g. Myers Wood (anomaly1) – Chapter 5.1.2.2.3 (b)) or very close together (e.g Westhawk Farm – Chapter 5.1.2.2.3 (a)), the anomaly shape may be irregular or elongate. In such circumstances a higher resolution survey may assist in the interpretation.

Although the centre of the furnace will be offset to the south of the anomaly (Chapter 4.0), experimentation has shown that the furnace will not be larger than the anomaly. Similarly, the form of the anomaly response may be used to estimate both the depth and width if the furnace is near the surface and some conditions, for example burial in wind blown sand, may nullify this point. The large amounts of material burying the furnace will increase the distance between the sensor and the furnace anomaly. Examination of the data from a high-resolution north-south traverse across the anomaly should confirm if the peak was flattened (deep) or well formed (shallow), and by using the method outlined in Chapter 4.0, an approximate depth of the anomaly may be determined.

Examination of the data values from a fluxgate gradiometer survey may give some indication of the furnaces state of preservation. The Ewecote (Chapter 5.1.2.2.1 (a)) example may suggest that the furnace walls are intact but without further evidence this is inconclusive. It has been suggested (Vernon *et al*. 1999a) that the highest values in the positive data cluster may indicate the position of the tuyere. The highest temperatures develop, and iron and its oxides tend to coagulate here and on cooling may still adhere to the furnace wall. The highest readings for the Myers Wood (anomaly 1) furnace (Chapter 5.1.2.2.3 (b)) were located on the east side of the data cluster. Excavation showed that this point corresponded with the only piece of intact furnace lining and it originally protruded the surface. Therefore the integrity / strength of the surviving furnace lining around the tuyere area, a mass with a high magnetic susceptibility and thermo-remanent magnetism, generate the high values. Similarly, for the Myers Wood (anomaly 3) furnace, the furnace lining was intact in the area where the tuyere was thought to be located. The lining was rich enough in iron for a magnet to adhere to it (*personal observation*). High fluxgate gradiometer readings (over 400nT) from shaft furnaces may indicate that substantial pieces of furnace lining are intact and may be associated with the location of the tuyere.

Some of the fluxgate gradiometer surveys (Ewecote (Chapter 5.1.2.2.1 (a)), Kyloe Cow Beck (Chapter 5.1.2.2.2 (a)), Myers Wood (Chapter 5.1.2.2.3 (b)) and Weldon (Chapter 5.1.2.2.3 (c))) have identified tapping channels and, by inference, the furnace tapping arch position. Values derived from the tapping channel can vary. High values, for example Myers Wood (anomaly 3) furnace where values exceed 100nT, may indicate that slag lies *in situ* in the channel. The thermo-remanent magnetisation in the slag is not randomised as it is in a slag dump, and so the magnetic field is not diminished by cancelling, and is further reinforced by the local magnetic field. In most examples the tapping channel will be a linear hollow of burnt clay and the positive data values will generally be lower than those produced by the furnace.

The West Hawk Farm (Chapter 5.1.2.2.3 (a)) and Weldon (Chapter 5.1.2.2.3 (c)) fluxgate gradiometer surveys both indicate that the furnaces were enclosed by other structures. In the former example, there is a weakly contrasting linear anomaly on a similar alignment to the furnace tapping-channel that may represent the position of walling. In the latter example, the survey suggests that building may have extended over the furnace area. Such structures are generally identified at low clipping ranges on sites where furnaces are often poorly preserved. In both the examples cited above, only the furnace bases remained and the negative bipolar response on the north side of the positive data was low, thereby not masking the subtle data.

The evidence from both experimentation and surveying would indicate that if a furnace is in a good state of preservation and not buried deeply, then it should be possible to obtain from the geophysical data (fluxgate gradiometer) the furnace morphology and the positions of the tapping channel and arch, and the location of the tuyere. If the furnace is in a poor state of preservation and low responses are produced it may be possible to identify surrounding structures.

Other industrial processes (e.g. brick, tile, pottery and glass production) use furnaces or kilns and produce magnetic anomalies on magnetometer surveys. These processes and the anomalies they produce are briefly outlined in Appendix 3.

5.1.3 Water-powered bloomeries

The application of waterpower to iron smelting meant that bellows and hammers could be mechanized and iron production increased. To accommodate those activities not only did the sites get bigger but also elaborate water management systems were constructed. In England this transition occurred in the fourteenth century (Cleere and Crossley 1995, 106). Waterpower meant that iron-working sites needed a reliable water source and that became a major factor in determining their locations. Apart from the Myers Wood example geophysically surveyed examples of water-powered bloomery sites are rare. In addition, very few have been excavated. For this reason the geophysical survey of Timberholme has been included in this category. It was probably a water-powered bloomery that evolved into a high bloomery, a proto-blast furnace (Chapter 5.1.3.2.2).

5.1.3.1 Excavated examples

Water powered bloomeries probably operated in most major iron producing areas of the British Isles. The Fasagh site in Scotland (Photos-Jones 1998) (Figure 3.3) has some characteristics of a water-powered bloomery, for example a substantial bloomery slag dump and water leats. However the lack of evidence for a furnace and the presence of anvils suggest that it may have been used for reprocessing iron, but even this process would have required a furnace or hearth. Clearly there is more research to be completed on this site.

Archaeological evidence is also compromised by the conversion of water-powered bloomeries into finery forges with the introduction of blast furnace technology in the 1500s (Tylecote 1990, 206). Only two examples of water-powered bloomeries have been excavated; one at Muncaster Head, Cumbria and one at Rockley Smithies, South Yorkshire. Both examples provide detail of bloomery infrastructure as well as furnaces and water wheel pits.

5.1.3.1.1 Muncaster Head

This site was excavated in 1967/68 (Tylecote and Cherry 1970). The construction of the bloomery was completed by 1637 and reported to contain a hammer and three bloomery hearths with bellows. Water would be channeled from and to the adjacent River Esk. Figure 5.1.66 shows the layout of the site and the main areas of excavation. The water channel adjacent to the bloomery was stone lined and a bypass channel ran around the south side of this area. This evidence and the discovery of fragments of a timber waterwheel identified the waterwheel's original location. Tylecote and Cherry (1970) suggested that the wheel was undershot and was 4.57m (15ft) in diameter, and 1.82m (6ft) wide. Adjacent excavations uncovered a working area with charcoal, ore, clay and slag debris. Haematite fragments on the south and west sides of the working area indicated the location of the ore store. A large number of furnace bottoms in the adjacent water channel suggested the location of the furnaces. To the north, a layer of charcoal up to 0.45m (18 inches) thick outlined the location of a sub-circular charcoal store (10.66m (35ft) diameter). The slag dump formed the southern boundary of the charcoal and consisted of tap slag and furnace bottoms. The relatively small amount of tap slag on the site was thought to indicate that it was removed at a later date for re-smelting in a blast furnace.

5.1.3.1.2 Rockley Smithies.

The Rockley Smithies bloomery site was excavated in 1964-66 prior to the M1 motorway being built over it (Crossley and Ashurst 1968). A silted up channel provided the initial evidence for a water-powered site. The layout of the site is shown in Figure 5.1.67. An ore roasting area thought to belong to an earlier phase in the site's development lies on the west side of a reservoir. The main bloomery area is located below the reservoir dam to the east. There are three furnaces. One was used for smelting. Crossley and Ashurst (1968) suggest that the absence of tapping channels for the remaining two furnaces indicated that they might have been used for reheating iron blooms.

The smelting furnace was built against a clay bank. It was about 1.0m in diameter and was formed from a clay-lined ring of stone to which cinder had fused. The internal diameter varied from 0.61 to 0.69m. The locations of both the tapping arch and the tuyere were evident. The central furnace was constructed on a stone plinth and had an internal diameter of 0.75m. The third furnace was poorly preserved.

To the east of the furnace building there was a further working area with a hearth and anvil. The floor surrounding the anvil was covered in hammerscale.

5.1.3.2 Geophysically surveyed examples

Only three medieval water-powered sites have been geophysically surveyed in Britain. Astill (1993, 107 - 108) detailed an earth resistance survey over the water-powered medieval smithy complex at Bordesley, West Midlands, that was conducted in 1984. A 1.0m resolution twin probe survey over $520m^2$ identified an area of high earth resistance that corresponded to a large level platform, a rectangular area of c10 by 8m with another area of c4 by 6m extending from it in a westerly direction. Areas of high values (c87 ohms) were correlated with stone structures. Further earth resistance traverses were conducted in 1991 and identified the route of a by-pass channel (Astill 1993, 109).

The other two sites, Myers Wood, West Yorkshire and Timberholme, North Yorkshire both contain the remains of smelting furnaces. The Myers Wood site was only discovered and geophysically surveyed in 2004 (Clay *et al*. 2004, 10 - 11). Timberholme was first recorded in 1972 (McDonnell 1972), and was first geophysically surveyed in 1995 (Vernon *et al*. 1998a, 1998b; McDonnell 1999).

5.1.3.2.1 Myers Wood

Ground conditions: Heavily wooded.

The Myers Wood water powered bloomery site, lies about 100m north of the Myers Wood bloomery site (Chapter 5.1.2.2.3 (b)). It lies on the east side of a stream and there is evidence of a small millpond from which a leat, now defined by a footpath, ran towards the water-powered bloomery. The location of the site is shown on the reconnaissance fluxgate gradiometer survey of Myers Wood (Figure 5.1.68).

Following the site's identification, high-resolution fluxgate gradiometer (0.25m resolution), magnetic susceptibility (0.5m resolution) and earth resistance (0.5m resolution) surveys were conducted and the results of the fluxgate gradiometer survey and interpretation are shown in Figure 5.1.69. The furnace is roughly 2m square and produced a maximum value of 980nT. Immediately to the northeast of the furnace there is a rectangular area approximately 8m by 5m. As it is aligned with the leat on its southeast side it is suggested that the bellows and hammers were located here, with the waterwheel located on the southeast side, where the leat is better defined on the survey. There is little evidence of extensive slag tips. The slag appears to occur as several clusters of positive data that produce values of less than 200nT. This may suggest that the slag has either been removed, or the bloomery was only operated for a short period.

The charcoal platform previously identified on the Myers Wood survey may be connected to the water-powered bloomery. Radiocarbon14 dating of charcoal fragments gives a date range of between 1480AD and 1680AD for the charcoal platform, later than the 12th to 14th century dates for the bloomery furnaces (Clay *et al*. 2004, 29). In addition a hollow way or track-way runs from the platform to the water-powered bloomery (Figure 5.1.68). It seems reasonable to speculate that the charcoal platform is contemporary with the water-powered operation and is part of the sites infrastructure.

A 0.5m fluxgate gradiometer survey was conducted over the charcoal platform and confirmed a sub-circular anomaly approximately 11m in diameter. Most positive values fell below 100nT. An excavation of the platform revealed a burnt clay surface about 15cm below the surface (Figure 5.1.70). A magnetic susceptibility survey (Figure 5.1.71) along a 9.25m trench on the burnt surface produced readings for the intensely burnt area of between 250, and just over 1000 x 10^{-5} SI Units. The highest values were recorded between 3.5m and 8m along the trench and probably indicated the area where the highest temperatures were generated, or used most frequently by the charcoal burners.

5.1.3.2.2 Timberholme, Bilsdale, North Yorkshire

Ground conditions: Rough pasture.

The Timberholme site lies on rough grazing land adjacent to the River Seph, near Laskill, Bilsdale. McDonnell (1972) identified a silted-up leat that trends roughly northeast / southwest across the site close to a low lying slag tip and an area of 'burnt soil' on the north side of the leat. Slag is exposed in the riverbank. The soil, mainly alluvium and exposed in animal burrows, overlies the slag dump and often exceeds 0.3m in thickness. There is an elevation change of about 1.5m across the site from the lowest (leat) to the highest points (slag dump). A plan of the site is shown in Figure 5.1.72.

Analysis indicates that the Timberholme furnace produced a slag that ranged in composition from a bloomery to blast furnace type (Vernon 1995, 113 and Finney 1997b), and it would be consistent with a high bloomery type of operation (Tylecote 1990, 213) that utilized both the *direct* and *indirect* processes (Tholander and Blomgren 1986).

A 1.0m resolution fluxgate gradiometer reconnaissance survey was carried out in 1995 (Figure 5.1.73). The leat traverses the site before turning into the river. The slag dump lies to the south of the leat and a complex rectangular structure to its north. This is interpreted as a building enclosing a furnace. Fluxgate gradiometer readings varied between -197 nT to 1391 nT over the slag, the higher positive data almost certainly being generated by furnace material (Vernon 1995).

A 0.5m resolution fluxgate gradiometer survey (Figure 5.1.74(a)) corroborates the positions of the features and anomalies noted on the reconnaissance survey. The cluster of positive data that corresponds to the furnace position is not circular and consists of two linear aligned anomalies of high positive data (greater than 1000nT), separated by the leat. This may suggest that the furnace structure collapsed in that direction. A 0.5m earth resistance survey (Figure 5.1.74(b)) confirmed many of the fluxgate gradiometer anomalies. The interpretation of the 0.5m resolution data in Figure 5.1.74(d) also suggested that a narrow channel ran into the square structure that housed the furnace.

A 0.25m resolution fluxgate gradiometer survey over the western furnace-related anomaly (E1) is shown on Figure 5.1.74(c). The data associated with this survey (Figure 5.1.75) show the positive anomaly to consist of a grouping of values close to and over 1000nT centred on a value of 2014nT.

A 1.0m resolution magnetic susceptibility survey was conducted over the same area with a 0.5m resolution survey over the square furnace structure (Figure 5.1.76). The slag distribution and the leat can be identified. Relatively low responses are associated with the square furnace structure, but there are small areas of high data suggesting some response to features noted on the fluxgate gradiometer survey. It is probable that after the site was abandoned, flooding deposited alluvium across the site. The thickness of this superficial material would affect the ability of the magnetic susceptibility equipment to respond to the underlying slag (Batt *et al*. 1995).

The interpretation of the survey is shown in Figure 5.1.77.

5.1.3.3 Discussion

Some similarities can be drawn between the Timberholme furnace site and the iron-working smithy complex discovered at the Cistercian Abbey of Bordesley in the English Midlands. The Bordesley project team excavated both a monastic watermill and workshops associated with iron-working, but as far as the evidence indicates it was not a water-powered bloomery site. There are no furnaces. From the archaeological data obtained a possible reconstruction of the water-powered mill was derived (Astill 1993, 270). This reconstruction is shown in Figure 5.1.78. The Cistercians probably commenced operating the Bordesley mill two centuries before the Timberholme furnace, but it is probable that some components of the Timberholme structures were similar and probably consisted of a stone furnace, housed in an open timber-framed building with a tiled roof.

Any water-powered operation is going to be subjected to severe erosion during times of flooding and the survival of any obvious structure is very unlikely. The geophysical surveys have shown that some elements can be identified including buried slag tips, water leats and the furnace structure. Whilst the geophysical survey at Bordesley identified just stone structures, possibly a higher resolution combined with different geophysical techniques would have provided more detail that would have contributed to the final interpretation. The value of geophysical surveys has been clearly demonstrated at Timberholme where the furnace housing has been identified and it is not unreasonable to expect similar responses from other water-powered bloomery sites.

In some respects the Myers Wood data is more revealing. The location of all the main components have been revealed and it is obviously a much smaller operation than

Timberholme. High resolution surveys over the interior of such structures are invaluable, For example, at Timberholme a small channel anomaly was identified running into the square structure that may represent the leat for the bellow's waterwheel and thereby indicate the position of the bellows within the square structure. Other components of the site should also be identifiable. It is known that charcoal deposits will produce high readings on earth resistance surveys (Vernon *et al*. 1998b). Tall furnaces would have also required a charging ramp of some description. Both the charcoal store and evidence for a charging ramp were prospected for at Timberholme and earth resistance and fluxgate gradiometer surveys were conducted on the high ground west of the furnace. To expedite the search, earth resistance surveys were conducted at 2.0m resolution. However neither survey recorded any significant anomalies.

5.1.4 Charcoal fired blast furnaces

The first documented operation of the use of a charcoal fired blast furnace in the British Isles was at Newbridge, Sussex in 1496 (Tylecote 1990, 214). By the mid-1500s the charcoal fired blast furnace had superseded most water-powered bloomeries that in some areas were being converted to fineries for refining the cast iron into a workable iron. There are many examples of excavated blast furnace sites and their operations are well recorded.

5.1.4.1 Excavated examples

The three excavated sites reported here provide examples of (i) a well-conserved charcoal-fired blast furnace together with the ancillary buildings including those used for ore and charcoal storage, (ii) a neglected but conserved site with a detailed excavation of the floors in the vicinity of the furnace, and (iii) a site where most of the structures are in a dangerous state and only just interpretable.

5.1.4.1.1 Duddon, Cumbria

The Duddon furnace (Riden 1993; Dunn 1998; Bowden 2000) was constructed in 1736. It ceased operations about 1871 and became derelict. In the 1980s it gained Scheduled Monument status and was excavated and consolidated by the Lake District National Park Authority. The furnace is virtually complete with a casting house on the south side, and the blowing-house (location of the bellows) to the east. The charging ramp has been reconstructed leading to the top of the furnace. Two substantial charcoal stores and a smaller ore store are located to the west of the furnace. Figure 5.1.79 shows the general layout of the Duddon site and Figure 5.1.80 contains a selection of photographs with explanations.

5.1.4.1.2 Rockley, South Yorkshire

The Rockley furnace**,** South Yorkshire, was constructed in 1652 and probably ceased operations in the early 19th century (Riden 1993, 103). Crossley (1995) excavated the casting floors and blowing house between 1978 and 1982. Figure 5.1.81 shows the general layout of the site. Whilst the water system is well defined, the locations of the charcoal and ore stores are not. They would have been located to the south of the site close to the charging ramp. The standing furnace stack is approximately 5m by 5m square and is located in an octagonal building roughly 18m by 18m. Much of the stone work is ashlar. The octagonal building also housed a water-wheel, adjacent to the bellows house, and a casting floor. The archaeological survey of the Rockley furnace is reproduced in Figure

5.1.82. The casting floor contains a stone lined pit 2.2m deep with an internal diameter of 1.47m, used for casting long hollow items, for example gun barrels.

5.1.4.1.3 Allensford, Northumberland

The Allensford furnace was excavated in 1977 (Linsley and Hetherington 1978). The excavation was confined to the walling, the furnace and a possible ore roasting / calcining furnace. The walling was identified as a retaining wall for a pond and the probable back wall of a blowing house. The excavation of the furnace revealed a pillar between the tapping arch and the blowing house. Part of the pillar's facing stones had been 'robbed'. The remaining infill consisted of rubble. It was concluded that removal of the facing stones had resulted in failure of the pillar leading to the partial collapse of the furnace. The hearth was lined with clay tempered with sand. A plan of the furnace (Linsley and Hetherington 1978) suggests that it was about 2.5m square. The calcining kiln is sub-circular in plan (about 2.5m diameter) tapering towards the base. It had a predominantly charcoal and ore infill with clinker and ash. Riden (1993, 123) indicates that the furnace operated from c1673 to early 1700s.

5.1.4.2 Geophysically surveyed examples

A survey at the Falling Creek Ironworks, Virginia, USA is the only other known example of a geophysical survey at a charcoal-fired blast furnace site, apart from the two conducted for this research.

5.1.4.1.1 Falling Creek, Virginia, USA

The Falling Creek blast furnace (1619-1622) was one of the earliest operating furnaces in the USA. Jones and Maki (2000) report that a previous investigation on the site found no conclusive evidence for structures or domestic areas. Slag and charcoal were discovered, but the site of the furnace was thought to be under an access road to the south. Fluxgate gradiometer, earth resistance and ground penetrating radar were used in the geophysical investigation. The earth resistance survey identified several linear features and an area of high earth resistance. On the fluxgate gradiometer data a positive anomaly with a large wavelength in profile was suggested as a likely candidate for the blast furnace at depth. Other anomalies probably were areas of slag. Overall the survey was inconclusive but was successful in confirming the extent of the slag dump. The shape of the dump would suggest that the initial observation that the furnace was to the south of the survey area was correct.

5.1.4.1.2 Rievaulx, North Yorkshire.

5.1.4.1.2.1 Background

The Rievaulx blast furnace commenced operations shortly after the dissolution of the Cistercian abbey of Rievaulx in 1538 and continued working until c1650-70 (McDonnell 1972). Documentary evidence indicates that an ironworks was already operating at Rievaulx prior to the dissolution, probably at Rye House south of the abbey (McDonnell 1999). Thus when the blast furnace was constructed an infrastucture was already in place that could provide both water power and abundant charcoal. The exact site of the furnace has not been fully established but field evidence would indicate that it was constructed on the southern flank of Furnace Hill, approximately mid-way between an identified ore roasting area and a slag tip. The latter was removed in the 1920s by the Ministry of Works while carrying out conservation work on the abbey. The adjacent abbey refectory is thought to have been used as a charcoal store (McDonnell 1999). A finery / chafery was also operating at Forge Farm near Rievaulx Bridge and possibly at Rye House (McDonnell 1972).

The Rievaulx 'canal' was a major diversion of the River Rye and runs through the survey area. It was the main drainage system in the monastic period bringing water to the Abbey from the north, and provided water for a fulling mill and iron-working activity. From the Abbey the 'canal' ran south to Forge Farm. Water would have been taken from it to power the hammersmithy at Rye House. South of the abbey it widens into an elongated lake which may once have served as fish pond. Three outlets run from the lake, an overflow to the River Rye, a leat to Forge Farm and the original south outlet to take water back to the River Rye. It was Rye (1900) who originally suggested it was a canal, and that it was used for transporting stone down to Rievaulx Abbey. However, despite attempts by various researchers (Weatherall 1954; Coppack 1986; Fergusson and Harrison 1999) to unravel the evolution of the water systems at Rievaulx no definitive interpretation exists.

5.1.4.1.2.2 Geophysical Surveys

Much of Rievaulx village falls within the scheduled monument area for Rievaulx Abbey. A prospection license was obtained from English Heritage to permit the surveys. The geophysical survey work to evaluate the blast furnace in Rievaulx Village has concentrated on four aspects; (i) the water supply; (ii) the location of the blast furnace; (iii) the ore roasting / storage area, and (iv) the distribution of slag. It is probable that the furnace was built close to a hillside to facilitate charging. However the village has undergone numerous changes since the blast furnace last operated. The area between the abbey and Furnace Hill has been partly built upon. Slag and charcoal is widely distributed on the southern flanks of Furnace Hill and roasted iron ore is common on the north side. The conjectured route of the 'canal' skirts the west side of Furnace Hill, but becomes indistinct near to Rievaulx Corn Mill to the west and becomes identifiable to the south in the abbey grounds.

Figure 5.1.83 shows the locations of the twenty geophysical surveys conducted in the vicinity of Rievaulx to identify features relating to the iron industry. Some areas have been eliminated by the surveys, but those around Furnace Hill (Figure 5.1.83, surveys 3, 13, 14, 15, 17) and Forge Farm (Figure 5.1.83, surveys 18, 19, 20) have identified the ore roasting area and a chafery complex, respectively. The geophysical surveys have not revealed any indication of finery activity at Rye House, but do give some indication of the water system.

5.1.4.1.2.3 The Water Supply

Ground conditions: Village gardens and rough pasture.

A 1.0m resolution fluxgate gradiometer and earth resistance survey (Figures 5.1.83 and 5.1.84, survey 2) on rough pasture land, immediately south-west of the 'Grooms Cottage' proved the extent of the 'canal' for an additional length of 60m. Figure 5.1.85 shows the results of the survey. Clipping the fluxgate gradiometer data from -100nT to 100nT highlights the responses from an iron pipeline that takes water to the Grooms Cottage. At the lower end of the data ranges (-10nT to 10nT) the route of the footpath can be identified (Figure 5.1.85(a)). Unfortunately the Rievaulx 'canal' is not a distinct feature. Figure 5.1.85(b) shows the clipped earth resistance data. On the wider clipping range of 10 to 34 ohms an area of high resistance data (>34 ohms) can be seen in the top right corner. This corresponds to an area of higher ground near to a septic tank. Two linear features run across the survey. The tighter clipped range enhances both of these features. A distinct zone of lower resistance values (<13.8 ohms) mimics the feature that runs from left to right across the survey. This zone corresponds to the extrapolated position of the Rievaulx 'canal' The diagonal linear features corresponds to the footpath. Figure 5.1.85(c) shows relief plots of the earth resistance survey.

Several surveys immediately south of the Corn Mill (Figures 5.1.83 and 5.1.84, survey 1) in the vicinity of the Stables failed to identify convincingly the 'canal'. Similarly, surveys east of the main road and south of Furnace Hill have not identified the route of the canal. This is due to several factors. The ground has been built upon and the surveys areas are too small to produce easily interpretable data. Only in the grounds of Rievaulx Abbey can the line of the 'canal' be determined with any confidence. A bank immediately east of the Abbey Shop and the foundations of the Fulling Mill define the width of the 'canal'. South of this point the canal is a clear topographical feature to its outfall in the River Rye. Figure 5.1.84 shows the probable route of the 'canal'through Rievaulx village.

A 0.5m resolution fluxgate gradiometer survey conducted immediately south of the mill (Figures 5.1.83 and 5.1.84, survey 1) across a rough track shows up several weakly contrasting linear anomalies that may represent the south bank of the 'canal', but the poor quality of the geophysical data due to noise, insufficient data and the influence of a building, makes any interpretation unreliable. Figure 5.1.86 shows surveys 1 and 2 and the possible continuation of the 'canal'.

5.1.4.1.2.4 The Blast Furnace

Ground conditions: Village gardens and rough pasture.

Initial survey work to locate the furnace was concentrated on a mound on the west side of Furnace Hill (Figures 5.1.83 and 5.1.84, survey 1). Its form suggested it may have been used as a charging ramp. It was not natural and probably composed of rubble. The results for this survey were inconclusive. Despite anomalies being found (Figure 5.1.86), there was no coherent pattern that would indicate any involvement with iron smelting activity. The data from the 0.5m resolution fluxgate gradiometer survey is shown as survey 1 on Figure 5.1.86.

It is probable that the furnace lay much closer to Furnace Hill between an identified ore roasting area and the slag tip that was originally adjacent to the Abbey refrectory. Unfortunately, geophysical surveys in this area, usually over small disjointed sections, are confined to gardens adjacent to the School House and the Mill House (Figure 5.1.83, surveys 3, 14 and 17), and parts of Rievaulx Abbey grounds (Figure 5.1.83, survey 13) that have been disturbed during clearance work by the Ministry of Works and the construction of septic tanks. Several strong positive anomalies have been identified on Furnace Hill. Only one linear anomaly has been identified adjacent to the vegetable plot of the School House (Figure 5.1.83, survey 17). However none of the geophysical information in this area has yet proved conclusive evidence for the exact location of the blast furnace.

5.1.4.1.2.5 Ore Roasting Area

Ground conditions: Orchard on a slope.

The ore roasting area (Figures 5.1.83 and 5.1.84, survey 3) was identified by finds of burnt ore in a vegetable garden. In the adjacent School House garden, near the entrance gate, the soil exceeds a depth of 2.0m and is rich in roasted iron ore and charcoal (Mr. Flintoff, School House, *pers. comm.* and G.McDonnell, *pers. observation*). Excavations revealed a sequence of burnt ore, charcoal and clay (floor horizon). On a 0.5m resolution fluxgate gradiometer (Figure 5.1.87) the ore roasting area is revealed by irregular bands of positive data. When all the data is clipped to -1000 to 1000nT only one point stands out (1791nT) adjacent to Mill House. This has probably been generated by an isolated piece of iron. It is only at the -100 to 100nT range that the area of burnt iron ore starts to become delineated on the survey. Very few readings exceed 200nT. At a clipped range of -50 to 50 nT the high values appear to adhere to a precise boundary. At the -10 to10nT range the area is geophysically ‘noisy’. It seems probably that the area proved by excavation, and also where the highest positive values occur, equates to the main area of ore roasting, whilst the lower ranges of data in the peripheral areas are produced by dispersed material.

5.1.4.1.2.6 Slag Distribution

Ground conditions: Village gardens and rough pasture.

Blast furnace slag is widely distributed throughout Rievaulx village, but it is not clear how much of this distribution occurred when the Ministry of Works removed debris from the abbey in the 1920’s/1930’s. Examination of records from this period at the Public Record Office, Kew, London (Files WORK14 and 31) and English Heritage records at Fortress House, London and Helmsley Station, North Yorkshire, provided little information on the precise location of the slag dumps. The location of a dump next to the abbey refectory is well recorded (Rye 1900; Anon 1913; Weatherall 1954). A 0.5m resolution fluxgate gradiometer survey in this area (Figure 5.1.83, survey 13) found no anomalies suggestive of a slag dump and it is concluded that the slag was totally removed by the Ministry of Works prior to landscaping the area.

The geophysical surveys in Rievaulx village have provided only scant information on the infrastructure that would have been required to support a blast furnace. Geophysical surveys in the Furnace Hill area tend to confirm that the furnace must have been located there, but the precise location has yet to be identified.

5.1.4.1.3 West Bretton, West Yorkshire

Ground conditions: Sculpture Park and rough pasture.

The site of the West Bretton furnace lies in the Yorkshire Sculpture Park south of Wakefield, West Yorkshire. The furnace was constructed about 1720 and ceased operating in about 1810 (Riden 1993, 101; Umpleby 2000, 76). It is believed the furnace was demolished shortly afterwards and the area became landscaped parkland for Bretton Hall. Surface evidence for the furnace is scant but includes a prominent water leat and tail-race with associated ashlar stonework, areas of red soil with fragments of roasted ore, soft patches of black soil with abundant charcoal fragments and a slag tip. One large piece of furnace lining was found close to the tailrace.

A 1.0m resolution fluxgate gradiometer (Figure 5.1.88) and earth resistance (Figure 5.1.89) survey was conducted over 1.5ha of parkland. Initially the work was concentrated around the leat, but progressed eastwards, as the extent of the site became apparent. On the west side a linear anomaly trended northeast / southwest and terminated at the leat. The anomaly corresponded with a slight change of slope and was interpreted as a field boundary. West of the boundary, ridge and furrow cultivation was evident on the surface. East of the anomaly the data is considerably more 'noisy'. An iron fence traverses the southern half of the survey. South of the fence on the flood plain of the River Dearne there is a tip of glassy slag. Immediately on the north side of the fence there is a hollow. The fluxgate gradiometer survey (Figure 5.1.88) suggests that it may have originally been enclosed by a structure approximately 18m wide perhaps not unlike the stone structure that surrounds the Rockley furnace (Figure 5.1.82). In the case of Bretton however, the stonework has been removed. A 0.25m resolution fluxgate gradiometer survey of the hollow has revealed little about the structures. The culverted route of the leat runs along the south side of the hollow and it is presumed from the Rockley evidence that the bellows would have been located here with the casting floor between the furnace and the slag dump. This interpretation may be supported by a rectangular anomaly on the east side of the slag dump that may have been a loading platform used for loading carts. There is no evidence for the furnace except for a short, weakly contrasting linear anomaly. However, as the furnace would have been above the removed floor level, a strong magnetic signature would not be expected. Fragments of iron-rich vitrified furnace lining would produce a strong magnetic signature, and two have been found at Bretton: one a small fragment about 30cm long, in the slag tip and another, considerably larger slab, on the west side of the hollow. The latter produced fluxgate gradiometer readings higher than 2047.5nT, the over scale default value. Immediately north-east of the hollow, a linear anomaly corresponds to the end of the charging ramp. Beyond this anomaly the interpretation becomes difficult. There are large amounts of roasted iron ore in the ground, signifying the approximate position of the ore store. No substantial linear anomalies were identified because at low clipping ranges subtle anomalies were masked by the higher responses. The earth resistance survey delineated areas of charcoal rich ground on the extreme north-east side of the site, signifying the positions of the charcoal stores. Beyond the charcoal areas a northwest / southeast anomaly appears to form a boundary to the site. The full interpretation of the West Bretton survey can be seen on Figure 5.1.90.

5.1.4.3 Discussion

The high bloomery and the charcoal-fired blast furnace represent a continuous operation requiring ample supplies of water, iron ore and charcoal. Both fluxgate gradiometer and earth resistance can be used with effect to identify the routes of water leats. The former technique will identify changes in the magnetic susceptibility of the later infill and the latter by variations in porosity. Magnetic susceptibility surveys however, are not as effective due to depth limitations, although every circumstance is different. On the Timberholme magnetic susceptibility data, the leat can be identified as a weakly contrasting feature but on the fluxgate gradiometer data it is very pronounced. Fluxgate gradiometer surveys will identify ore roasting and storage area, due to the large amount of magnetic minerals (e.g. magnetite) produced by the roasting process, for example at Rievaulx and West Bretton. Whilst fluxgate gradiometer surveys are impervious to charcoal, earth resistance surveys can identify such deposits. The high resistance values result from the low moisture content of charcoal caused by good drainage through the charcoal deposit and to a lesser extent the charcoal removing moisture from the surrounding material.

Both the archaeological and geophysical evidence suggest that blast furnaces were enclosed by a protective structure. This was common practice with later furnaces, for example at Furnace, Ceredigion (Riden 1993, 69 - 71). The structure at Timberholme may have been an open but roofed structure whilst that at West Bretton was more substantial. Geophysical evidence for the position of all the surveyed furnaces is sparse. This is probably because the furnaces were located above ground level and any surviving stonework at ground level would be unaffected by the high temperatures from the furnace. The furnace lining or 'burr' is frequently found, for example at West Bretton and Duddon, and it is fragments of the 'burr' with a distinct magnetic signature than can produce very high readings on fluxgate gradiometer surveys. Cast iron lintels were used in furnaces to support stonework over the hearth area, for example at Rockley, and they would also produce a high magnetic signature if present. However given the split and irregular form of the high positive data at Timberholme, the high values are probably produced by furnace lining.

5.1.5 Finery and chafery

Tylecote (1990, 206) refers to the conversion of the water-powered bloomeries to finery and chafery operations, with the advent of the charcoal-fired blast furnace. This implies that the requirements are similar in both operations. The furnace was similar to a bloomery hearth but usually square or rectangular in plan (Tylecote 1990, 218).

Walline (1997) describes the finery process in detail. Within the hearth, cast iron would be subjected to a temperature of about 1500ºC. The carbon would be oxidized and an iron bloom would form and slag tapped off. A large slag block known as a 'mosser' was the main by-product. The chafery was a similar type of hearth where the iron bloom was forged into a bar. It was probably common for both operations to be conducted in the same building. A finery forge at Ardingly, Sussex (Tylecote 1990, 219) contained both types of hearth and water-powered bellows. A separate waterwheel drove a hammer for forging the bloom. For most forging or smithing operations it is common to find spreads of hammerscale around the anvil, for example at Burton Dassett (Figure 3.2) and Westhawk Farm (Figure 5.1.43).

5.1.5.1 Geophysically surveyed examples

The only two known examples of geophysically surveyed finery and chafery sites are part of this current research. Both are close to the Rievaulx blast furnace and are typified by 'mosser' tips (Walline 1997).

5.1.5.1.1 Rye House, Rievaulx, North Yorkshire

Ground conditions: Garden, orchard and pasture.

Rye House lies about 500m south of Furnace Hill in Rievaulx village and is recorded in the Rievaulx Abbey dissolution documents of 1538/40 as a hammersmithy (McDonnell 1972, 1999). The field to the north of Rye House was known as 'Dam Field' (North Yorkshire Record Office, Northallerton, Feversham Estate Records) suggesting it may have once contained a reservoir or a fishpond. Early ordnance survey maps suggest that there was a linear hollow in the field but this no longer exists. The *'Dam Field'* was covered with rubble from Rievaulx Abbey when it was cleared and conserved by the Ministry of Works in the 1920's/1930's. Opposite Rye House, there is a tip of furnace bottoms up to c1.0m thick covering the adjacent bank of the River Rye. The minor road from Rievaulx to Rievaulx Bridge also goes over a small hillock immediately opposite Rye House. Iron fencing, farming machinery and sundry metallic implements rule out the use of a full fluxgate gradiometer survey in the immediate vicinity of Rye House. However various surveys have been conducted in the general area and these are shown on Figure 5.1.83, surveys 7,8,9 and 10.

Figure 5.1.91 shows the geophysical surveys conducted around Rye House. Fluxgate gradiometer surveys in both *'Dam Field'* and the adjacent cricket field have revealed no evidence of iron-working. Surveys of the small garden immediately south of the house have been inconclusive. Only an earth resistance survey in a small field between the road and the river has identified a weak linear anomaly. It is on a similar alignment to the original hollow in *'Dam Field'* and might represent a tailrace. The iron-working operations were probably conducted in an area under, or immediatly to, the east side of the road adjacent to the small hillock that probably represents a slag tip.

In this example the geophysical surveys could only identify possible components of the finery's infrastructure. The remains of the finery probably lie under Rye House and the adjacent buildings.

5.1.5.1.2 Forge Farm, Rievaulx, North Yorkshire.

Geophysical surveys at Forge Farm, 1000m south of Rievaulx village, have provided evidence to indicate that the cottage was the location of the chafery for the Rievaulx blast furnace (Rye 1900; Weatherall 1954; Vernon *et al*. 1998b). Three areas designated as Forge Farm, Forge Farm East and Forge Farm North (Figure 5.1.83, surveys 18, 19 and 20 respectively) have been surveyed with both fluxgate gradiometer and earth resistance methods at 1.0 and 0.5m resolution and are separated from each other by either the minor road from Rievaulx to Helmsley or the Rievaulx 'canal'. The following description is taken from Vernon *et al*. (1998b).

5.1.5.1.2.1 Forge Farm

Ground conditions: Rough pasture dominated by a large tip of 'mossers'.

This is a prominent tip composed of slag and hearth bottoms, 1.6m high, located immediately east of Forge Farm Cottage. A fluxgate gradiometer survey (0.5m resolution) results (Figures 5.1.83, surveys 18 and 5.1.92) identified three distinct zones. The slag tip produces data ranging between -350 to 350nT. A peripheral zone to the tip has between -75 to 75nT with slightly elevated values on the north side generated by patches of hammerscale in the topsoil. The area immediately south of the tip is relatively quiet and the range falls to -10 to 10nT. The central area and thickest part of the tip is delineated by the greatest data variation between -2011 to 2035nT.

An earth resistance survey (0.5m resolution) was also carried out over the north side of the tip. Problems with contact resistance were experienced due to the dry and loose nature of the tip material. Resistance values generally exceeded 300 ohms. Areas greater than 500 ohms were encountered which follow the tip contours. After a wet winter, the tip was resurveyed and the grid extended south and around Forge Farm Cottage. Resistance values were lower by a factor of 10. Despite experimentation, by altering remote probe location and spacing (Clark 1990, 46) it was not possible to duplicate any of the high values recorded in the previous year. Values for the whole survey were generally between 20 ohms to 30 ohms, but as low as 10 ohms in areas of wet ground. High values had a similar distribution pattern to that previously observed, following the tip's contours in curving belts. Animal activity in those areas has brought soil to the surface. It is black and contains abundant charcoal and produced values between 50 ohms and 100 ohms range. Figure 5.1.93 shows the earth resistance data. The earth resistance survey covered both the north and south sides of Forge Farm Cottage and successfully identified the route of a leat. A further 1.0 resolution survey of five linearly aligned grids in the field to the south confirmed the continuation of the leat.

A 1.0m resolution magnetic susceptibility survey over the tip is shown in Figure 5.1.94. High magnetic susceptibility values (greater than 800 x 10^{-5} (SI)) were recorded on the north, east and south sides of the tip and are coincident with outcropping slag. An area of lower values (below 300 x 10^{-5} (SI)) on the extreme southeast side of the survey represents non-slaggy material, probably from the original ‘canal’ bank. Middle range values (300 x 10^{-5} to 600 x 10^{-5} (SI)) extend from the centre of the tip westwards along a gentle slope. It is thought that this was the route along which material was brought onto the tip and could be indicative of an increasing thickness of soil over the slag.

5.1.5.1.2.2 The Forge Farm East Survey

Ground conditions: Rough pasture.

The Forge Farm East site lies on the south side of the Helmsley road and immediately east of the 'canal'. A small slag tip partly excavated, about 1m high, lies adjacent to the road. The surrounding field is cultivated pasture. "Mossers" and soft patches of charcoal rich soil are evident.

A fluxgate gradiometer survey (0.5m resolution) identified most of the key components of the site. The slag tip at the north end of the survey produced values varying from 767 to 1254nT at the thickest part of the tip. Elsewhere, the values were generally in the range of -5 to 5nT.

Figures 5.1.83, survey 19 and 5.1.95 shows the fluxgate gradiometer survey. The clipped data range from -500 to 500nT highlights the highest values produced by the tip and the adjacent boundary fence. At a range of -5 to 5nT several parallel linear anomalies are visible running northeast / southwest across the survey and trend toward the slag tip. They have been interpreted as pre-tip ridge and furrow features.

A 0.5m resolution earth resistance survey over the same area produced values between 9 to 53ohms. The higher values occur on the west and north sides where the slag tip and the east embankment of the ‘canal’ are found. The lower values (9 to 27ohms) lie on the low-lying ground to the east. This area is probably closer to the water table and may also have a different soil composition. Highest values are associated with the slag tip. The crescent feature produced by the removal of slag can be identified on Figure 5.1.96. One cluster of slightly higher data corresponds to an area of soft black charcoal-rich soil.

5.1.5.1.2.3 The Forge Farm North Survey

Ground conditions: Pasture.

The Forge Farm North site lies within the Rievaulx Abbey scheduled monument area on the north side of the Helmsley road, and immediately west of the ‘canal’. A conspicuous nettled mound abuts the ‘canal’ embankment with abundant charcoal fragments. Although there is no evidence of slag, this survey was conducted to determine if (i) the position of the leat system that would have conveyed water to the Forge Farm chafery could be identified, and (ii) activities associated with the Forge Farm chafery extended into this area.

Fluxgate gradiometer and earth resistance surveys (Figure 5.1.83, survey 20) were conducted at 1.0m resolution and 0.5m resolution immediately west of the ‘canal’. On the west side of the fluxgate gradiometer survey values were typically between -10 and 10nT. On the east side the range increased to -20 to 20nT. The southeastern corner of the survey produced the highest variations, -103 to 224nT. This was confined to a narrow band adjacent to the road and is attributable to redistribution of slag from the dump at Forge Farm immediately to the south of the road. Figure 5.1.97 compares the two surveys with the data clipped between -20 to 20nT. A linear anomaly trends northwest / southeast across the eastern side of the survey corresponding to the centre of the canal embankment and may represent the embankment core material. In the southeast corner of the survey, adjacent to the embankment, there are two parallel linear anomalies that apparently disappear into the area of slag. They are on a similar trend to anomalies identified on the Forge Farm East survey and probably represent the remnants of pre-slag ridge and furrow. A ditch running along the field side of the boundary hedge represents the remains of the leat that conveyed water to Forge Farm. It appears in the southwest corner of the survey before turning south towards the farm.

The processed earth resistance data are shown in Figure 5.1.98. A roughly triangular shaped area, in the southeast corner of the survey consists of values between 35 and 103 ohms. The ground there is composed of black charcoal rich soil that is soft underfoot and was probably a charcoal storage area.

The interpretation of the Forge Farm complex and the water routes identified are shown in Figure 5.1.99.

5.1.5.1.2.4 Discussion on the Forge Farm site

The spread of slag at Forge Farm suggests that the slag dump was once more extensive, but probably confined to the area south of the road. Rye (1900) mentions that the slag '*has been used for years*' to repair the roads a fact confirmed by the likelihood that the Forge Farm and Forge Farm East slag dumps were once one dump that covered the 'canal'. On the north side of the Forge Farm dump there is a circular indentation with a high response on the fluxgate gradiometer survey that was originally thought to represent a structure (Vernon 1995). There is, however, no supporting evidence from either the earth resistance or magnetic susceptibility data. It seems more likely that this feature may be the product of slag removal and the higher values associated with the circular feature are produced by a large piece of iron rich furnace bottom under a thin covering of soil. The extent of the slag across the 'canal' to Forge Farm East indicates that the dump may have originally filled the canal. In this area, the west bank of the 'canal' is not discernible suggesting it has been breached. Immediately south of the breach, there is a mound of non-slag material (responses are considerably lower than those produced by the slag) probably composed of material removed from the canal bank. Further evidence of slag removal can be seen on the Forge Farm East fluxgate gradiometer and earth resistance surveys where there is a distinct crescent shaped anomaly corresponding to a depression on the eastern face of the tip. The Forge Farm North fluxgate gradiometer data have confirmed that there is a narrow band of slag immediately to the north side of the road. Its relationship with the slag tips to the south of the road is unclear, but it may suggest that the tip once extended over the area now occupied by the road and across the canal. The thickest part of the slag tip lies immediately east of Forge Farm Cottage and is identified by extreme variations of fluxgate gradiometer data. The highest recorded values occur in this area with the instrument occasionally recording over-range values. The Forge Farm slag, by its mode of formation (the final manufacturing process to produce a malleable iron) is rich in iron oxide (76.3% - Vernon *et al.* 1998a) this may support the observation by Al-Mussawy (1990) that the thickness of the slag can affect the magnitude of the magnetic response. The surveys confirm the visual extent of the slag tip and that tipping was tightly controlled with very little spread. The slag was brought onto the tip from a westerly direction, confirmed by the steep eastern tipping face of the tip.

The Forge Farm earth resistance survey identified the embankments of the leat, on the north and south sides of Forge Farm Cottage. It is probable that they align with a possible waterwheel pit that was uncovered during the building of an extension to the cottage (R. Teasdale, Forge Farm Cottage, *pers. comm.*). The resistance survey has also identified bands of high value positive data, predominantly on the northwest side of the slag tip, that correspond to charcoal rich soils with some hammerscale. As these high earth resistance areas generally follow the contours of the slag dump it is thought that they may result from lighter material from the tip becoming dispersed by runoff around the base of the tip. Rye (1900) comments '*that the ground in front of the cottage is so highly charged with charcoal that it easily takes fire and burns for days*'. The area of high earth resistance values on the Forge Farm North survey was undoubtedly a charcoal storage area. This was confirmed in 1998 when the field was ploughed up, to reveal a triangular shaped charcoal deposit that corresponded exactly to the area of high earth resistance data (*personal observation*).

At Forge Farm East the fluxgate gradiometer survey revealed four sub-parallel linear anomalies trending east-north-east/west-south-west immediately south of the slag tip. The northern two appear to be terminated by the tip but actually have been covered by the slag. Similarly, anomalies on the same trend were identified on the Forge Farm North survey under the charcoal store. It is possible that they may represent pre-tip ridge and furrow cultivation, which can be occasionally seen elsewhere in the area, for example northeast of Rye House (*personal observation*).

5.1.6 Forge and Bloomsmithy

Forging and bloom-smithing are very similar operations requiring iron or iron bloom respectively, to be hammered on an anvil. Whilst the processes are relatively well recorded (Schubert 1957; Goodhall 1981; Tylecote 1984, 1990), there are very few sites that have been excavated or geophysically surveyed. This section will include examples from the Roman to the medieval periods. Bloomsmithies ceased with the introduction of the charcoal-fired blast furnace, but forges are still in use to the present day. Forges were once common features on a variety of industrial sites, notably mines, for example Samson Mine, Vosges (Grandemange 1990) and Old Gang Mine, North Yorkshire (Cranstone 1992). Geophysical surveys of such sites however are rare, and those published (Cech and Walach 1990; Ancel and Fluck 1990) showed anomalies associated with slag dumps usually at the side of the forge.

5.1.6.1 Excavated and geophysically surveyed examples of bloomsmithies and forges

The examples in this section have been included to illustrate the processes and their geophysical responses rather than provide examples from a specific technical phase or historical period.

5.1.6.1.1 Westhawk Farm, Ashford, Kent (a bloomsmithy)

Ground conditions: Excavated surface.

This Roman town on the south side of Ashford, Kent at Westhawk Farm was discovered in 1997 (Philp 1998). A geophysical survey at 1.0m resolution identified an industrial area. Excavation suggested that the industrial area was a bloomsmithy. The associated furnaces have already been described (Chapter 5.1.2.2.3(a)). The smithy covers an area of approximately 10m by 15m. It had a roof that was supported by eight regularly spaced timber posts. The furnaces at the southwest end of the structure were probably partly covered by the roof and the whole structure was surrounded by a gulley system. Close to the furnaces is a ditch backfilled with furnace debris. Several clay pits are located immediately to the southeast. Internally there is a small hearth and in the centre a high concentration of hammerscale on the floor. An assessment of the slag (Paynter and Bayley, n.d.) confirmed that the site had been used for bloomsmithing.

The geophysical survey results from the Westhawk Farm smithy are shown in Figures 5.1.36 to 5.1.43. Two fluxgate gradiometer surveys at 0.5 and 0.25m resolution, respectively, were conducted over the smithy area (Vernon 2000a). Between –100 to 100nT a pseudo-rectangular anomaly is well defined. An area in the middle produced values in excess of 2000nT causing the instrument to default and to go off scale. The excavation had previously revealed concentrations of hammerscale at this point and probably coincided with the anvil location. The 0.25m resolution survey enabled the rectangular anomaly to be identified at -400 to 400nT. Several smaller anomalies, possibly postholes, were also recognised. An anomaly identified on the 0.25m resolution survey connects the 2000+nT anomaly with the hearth. A demonstration at Rievaulx Abbey during 2002 of iron forging techniques showed that hammerscale was actually re-deposited by the boots of the blacksmith as he walked between the hearth and the anvil (*personal observation*). It is probable that the anomaly at Westhawk Farm was produced in a similar manner.

5.1.6.1.2 Myers Wood, Huddersfield, West Yorkshire (a bloomsmithy)

Ground conditions: Heavily wooded sloping ground.

The recent excavation at Myers Wood (Vernon *et al*. 2003) revealed an assemblage of platy slag with spheroidal and flake hammerscale, consistent with a bloomsmithing operation. Some of the slag contained a high proportion of magnetite (Godfrey *et al*. 2003). It had been established from the initial 1.0m resolution survey (Chapter 5.1.2.2.3 (b)) that a structure had once stood at the southern end of the site. An excavation trench had been positioned at a corner of it, with the intention of finding dateable pottery. Dateable pottery fragments indicated the site was working in the 13th century. An examination of the 0.25m resolution fluxgate gradiometer survey revealed a rectangular anomaly that surrounded a cluster of positive data that produced a high value of 560nT (Figure 5.1.100). Examination of the ground in this area revealed several burnt stones protruding from beneath a tree. The tree has since been felled and the area excavated to reveal the hearth structure shown in Figure 5.1.102.

The magnetic susceptibility data, from a survey by A. Powell (2003, Department of Archaeological Sciences, University of Bradford), also shows the bloomsmithy area very distinctly. An area approximately 5m by 8m on the 0.25m resolution survey corresponds to the bloomsmithy on the fluxgate gradiometer data. The data was clipped to various ranges as shown on Figure 5.1.101 to highlight the anomaly. Within the smithy area data is generally in the range 600 to 1000 x 10^{-5} (SI) with occasional spikes of data over 1000 x 10^{-5} (SI). Some of the high values fall close to the 560nT anomaly. Around the rectangular area values are generally less than 80 x 10^{-5} (SI). A slag tip abuts the smithy on the northeast side. There is a distinct transition zone around the perimeter of the smithy suggesting lateral spread of high magnetic susceptibility material from the smithy area.

5.1.6.1.3 Bordesley (a water-powered forge)

Bordesley (Astill 1993) is a very detailed excavation of a water-powered medieval forge. The first phase of construction dates to the mid-12th century when a workshop was constructed on a low platform. During the intervening years to its cessation, in the late 14th or early 15th century, the site went through many changes. Hearths were rebuilt, re-sited or removed and the waterpower system was modified. The forge was also rebuilt after a fire in the late-12th century (Astill 1993, xiii). The excavations provided evidence to show how the forge had evolved. The well-preserved timberwork, predominantly of the leat system, provided material for dating. On the working platform, the bases of various hearths were identified constructed of pitched tile or stone. Layers of ash and charcoal surrounded the hearths as well as metalworking residues including scrap and part-forged iron (Astill 1993, 33).

5.1.6.1.4 Burton Dassett, Warwickshire (a forge)

Burton Dassett was probably the first forge to be geophysically surveyed in Britain (Mills and McDonnell 1992; Bayley *et al*. 2001). After 10 years the innovative approach used for this survey has not been surpassed. The purpose of the survey was to establish if a building had been used as a smithy by evaluating spreads of hammerscale. The building had been excavated down to a poorly defined floor level. Samples (200g) were taken every 0.5m from the earth floor and walls. Sampling transects were also conducted outside the area to evaluate the decrease in hammerscale. There was a correlation between the magnetic susceptibility and the weight of magnetic material extracted from the samples. The results of the surveys are shown in Figure 3.2. It shows that some sections of the wall and floor contain high amounts of hammerscale, presumably from flying off the metal during hammering. Magnetic susceptibility values were high in areas containing hammerscale. The samples from the hearth area contained small amounts of hammercale. The results were consistent with the building being used as a smithy.

5.1.6.1.5 Discussion on bloomsmithies and forges.

Finney (1997a) discusses the ephemeral nature of iron-smithing structures referring to McDonnell (1988). The principal structures, the hearth and the anvil, are built up to waist height with few sub-surface features. Mine forges, for example at Cyffty Mine, Betws-y-Coed, Aberconwy, North Wales, have a simple hearth structure and the anvil may consist of little more than a vertically placed tree trunk on which a piece of iron was fastened (*personal observation*). Eventually the wood will rot and the only clue to the anvil's location is therefore the hammerscale concentration and a 'post hole'. Finney (1997a) surveyed a modern forge at the Ryedale Folk Museum, North Yorkshire that had been operating for 30 years. The survey confirmed a high magnetic susceptibility around the anvil and an enhanced susceptibility between the hearth and the anvil. Finney (1997a) also noted that the magnetic susceptibility increased where metal working activity took place, for example sawing and filing operations.

Despite the few surveys of bloomsmithies and forges, geophysical surveys have proved invaluable in their interpretation. Whilst such a building may not be recognised when it is out of context, i.e. not on a related site, for example on a mine or bloomery site, a fluxgate gradiometer survey could identify spreads of ‘spikey’ data associated with it. A high-resolution survey should also show up the location of both hearth and anvil (c.f. Westhawk Farm). Magnetic susceptibility surveying is also invaluable as this technique will show up subtle variations in the near ground conditions when examined in conjunction with fluxgate gradiometer data, for example at Myers Wood. The use of earth resistance methods could also be invaluable for identifying walls.

5.1.7 Miscellaneous sites

The following example has been included to show that the presence of slag does not necessarily mean that it is directly associated with smelting at the location it was found.

3.1.7.1 Milford on Sea, Hampshire.

Ground conditions: Wooded area with a few open spaces.

The presence of blast furnace slag beneath an uprooted tree at Milford on Sea, Hampshire provided a unique opportunity to geophysically evaluate the site of a possibly unrecorded blast-furnace (Vernon 1998c). The only other recorded blast furnace site in this area was at Sowley, about 9 kilometres to the east-north-east of Milford (Riden 1993, 142). The land around Milford on Sea has an ample timber supply for charcoal production, a local source of iron ores from the Oligocene strata, and a stable water supply. The word “myne” has been applied to a shoal just off the coast, suggesting that the iron ore exposed in the cliffs may once have been extracted and shipped away. This was once a common practice along many parts of the British coastline, for example on the ironstone outcrops between Staithes and Port Mulgrave, North Yorkshire (Owen, 1985, opposite 32 photographs 1a,b and c).

The slag was discovered in the valley bottom and a trial pit had been dug to try and evaluate its extent. A 0.5m resolution fluxgate gradiometer survey covered the area where the slag was first discovered. The highest range of values with isolated individual iron spiking produced extremes of -149 to 339nT. Generally the overall range of data ranged between -30 to 30nT. Six auger holes were drilled in the vicinity of the upturned tree roots to determine the extent of the slag. All the holes were drilled down to a distinct band of grey clay which was thought to represent the natural sub-soil. The auger holes proved the slag to be of limited thickness (30cm) and extent (over a 10m wide area).

Archival information suggested that an ornamental pleasure garden had been partly constructed in the area in the 19th century (Sophie Jundi *pers. comm.*) The presence of a mature 'Monkey Puzzle' tree testified to those endeavours and so it is suspected that the blast furnace slag was brought in for pathways or as an ornamental stone. The use of blast furnace slag for paths and ornamental purposes is not unknown and examples can be found in paths at Bretton Sculpture Park, (Wakefield, West Yorkshire) and Leeds Castle, Kent (G. McDonnell *pers. comm.)* or even as a walling inlay.

5.2 Lead

5.2.1 Introduction

Galena (PbS), the primary lead ore, has a wide distribution predominantly in the Lower Carboniferous rocks of the Mendips, the Pennines and northeast Wales; and in the Ordovician and Silurian rocks of Shropshire, north and central Wales. Galena can have a relatively high silver content that may have added impetus to its exploitation by the Romans. Lead has been consistently mined in Britain since the Romano-British period (Raistrick 1928; Dunham *et al*. 1978, 263 – 317; Tylecote 1990, 54 – 80; Ixer 2003, 99).

5.2.1.1 Smelting Techniques.

Very little is known about early lead-smelting technology in Britain. Lead artefacts have been found in Iron Ages villages (Blick 1991). The earliest evidence for lead smelting activity appears in the Romano-British period. Attracted by the high silver content of the lead ore evidence can be found predominantly in the Mendips, the Peak District and northeast Wales. It is probable that the Romans employed shallow bowls scooped out of clay of about 1.0 to 2.0m in diameter, as for example at Scarcliffe Park, Derbyshire (Tylecote 1990, 57; Lane 1973, 21) and at Duffield, Derbyshire (Willies 1990,1). It is unlikely that there was any change to smelting techniques until the introduction of the water-powered smelt mills in the mid-1400s (Murphy and Baldwin 2001, 3; Tylecote 1990, 56). Prior to this, air was introduced into the lead smelting process by natural draught or by manually operated bellows (Tylecote 1990, 57).

Most researchers regard medieval lead smelting as a two-stage process. Gill (1992a) describes the basic method employed. In the first stage the lead ore was heated to between 600 to 800°C in an oxygen rich environment in a bale (or bole in Derbyshire). This was usually constructed on high land to catch the prevailing wind, and it was essentially a wood bonfire onto which the lead concentrate was placed. Barker and White (1992) have studied the location of bale sites in Swaledale, North Yorkshire and shown that most are located on southwest facing escarpments to catch the prevalent winds. Prior to the introduction of water-powered ore dressing methods, the galena would have been hand-dressed and would have contained very little gangue material. A comprehensive study by Murphy and Baldwin (2001) has examined bale sites in Swaledale and shown that many are ephemeral in nature. They concluded that bales were used for batch smelting small quantities of pure galena.

Raistrick's (1928, 1975) description of a bale at The Winterings, Gunnerside, Swaledale as a circular dry stone walled construction with an external diameter of c1.52m has been cited as a typical bale (Tylecote 1990, 57 – Figure 23; Clough 1962, 36 – Figure 16; Raistrick 1975a, 23). Unfortunately the exact location of this bale has never been identified. Raistrick's example (1928, Plate XIV) may be the exception rather than the rule. Most of the bale sites were identified by slag spreads and pieces of fire-reddened sandstone spotted or coated with slag or lead (Murphy and Baldwin 2001). Kirkham (1971, 193) reproduces Raistrick's original sketch of the Winterings bale. The latter sketch (Figure 5.2.1) can probably be taken as a true representation of the bale when Raistrick first identified it, rather than Raistrick's stylized interpretation (Figure 5.2.2). The resulting slag is usually grey and still contains lead. Gill (1986) and Blanchland (1981) refer to the one adaptation of the bale process, the *turnebole*. This was a hearth c1.50m high set upon a timber platform that could be rotated to face the direction of the prevailing wind. This would eliminate irregularities in consumption produced by changing wind directions. How successfully or widespread this technology was adopted is not known or fully understood.

The second stage (Gill 1992a) may have used a 'blackwork' oven. This process involved re-heating the 'grey' slag using foot-operated bellows to generate higher temperatures (1100º and 1200ºC). This produced molten lead, and the molten slag generally floated on the metal. The slag is referred to as 'black' slag and there is ample documentary and archaeological evidence to indicate that 'grey' slag and even reused 'black' slag was smelted in this process (Gill 1992b).

There is evidently some confusion between the 'bale' and 'blackoven' processes. Blanchland (1981, 78) suggests that Raistrick's bale (Figure 5.2.2) is a 'blackwork' oven and illustrates the process by adding bellows to the Winterings bale (Figure 5.2.3) to achieve the higher temperatures.

In Derbyshire, the 'bales' were frequently referred to as 'boles' (Kirkham, 1971). They are commonly found in the Peak District and some may have been square structure about 1m in diameter and clustered together (Rieuwerts, 1998, 27). Kirkham (1971, 191) notes that they were still in use well into the 17th century in Derbyshire. Documentary sources give informative descriptions of Derbyshire boles. Kiernan and Van de Noort (1992, 19) reproduce a 16th century description: '*the bolinge place was built upon a hill and walled with stone on the owt sides and the back about xx foot wyde…*'.

Elsewhere in Britain bales / boles are relatively unknown. Despite extensive lead mining in north and central Wales very little evidence has been found to indicate this technology was being used. Only a recent discovery at Penguelan, Cwmystwyth, Ceredigion provides evidence of their use in Wales (Timberlake 2003, 13 - 14). Two types of furnaces were identified. One was a type of walled structure built directly on turf. Very little evidence remained except for spreads of vitrified rock and a lead rich slag. The second furnace was a clay-lined bole scooped out from the side of a gravel ridge. A clay-bonded wall had been constructed around it. This furnace had been re-lined on several occasions. A tapping channel about 8.0m long ran downhill with burnt turf and lead still *in situ*. A C14 date for the bole suggests that the site may have been operated by the Cistercian order of Strata Florida Abbey at the end of the 12th century (Timberlake 2003, 13 - 14).

There is also some evidence to suggest that towards the end of its era the bole was undergoing transformation. The Totley bole (Kiernan and Van de Noort 1992) is rectangular and has two 20m long casting channels that trend down slope to a casting area. This seems very elaborate for the processes involved and clearly this site needs further investigation, as the Totley bole is not typical and may represent the introduction of new ideas into the lead smelting process.

In the ore-hearth process (Figure 5.2.6) that superseded bole technology, air was introduced into the hearth with water-powered bellows. Gill (1986) describes a mill at Beauchief near Sheffield that was operating c1581. It used two furnaces with water-powered bellows to smelt lead continuously. The hearth was made of stone (48in (122cm) high by 15in (38cm) broad by 18in (46cm) long) and a stack carried the fumes away. Lead ore concentrate was directly mixed with the fuel (coal, wood or peat) (Gill, 1992a), and when sufficient molten lead had been released the slag and charcoal would be removed and the molten lead ladled out. Larger furnaces incorporated a tap hole (Tylecote 1990, 57). Ore hearth mills can be found in most lead mining areas. The smaller mills (See Figure 5.2.4) may contain one ore hearth with a short chimney or flue terminating at a chimney. The majority of the larger multi-ore hearth mills, certainly in the Northern Pennines, had long flue systems sometimes over a kilometre in length, terminating at a chimney. This adaptation was used to (i) remove the lead fumes, (ii) to create a forced draught, and (iii) for the condensation of lead. To assist in the latter process, condensers were added. They usually consisted of chambers in which walling provided a larger surface area for metallic lead to condense from the fumes. Clough (1962) and Raistrick (1975b) record many examples of ore hearth mills in the Northern Pennines. Ancillary buildings around the site may be used for storing lead ore and fuel. In the Northern Pennines peat was used at many of the mills necessitating the construction of storages houses. The peat house at the Old Gang Mine, Arkengarthdale, North Yorkshire, is probably the largest in the British Isles with a length and width of 118m and 6m, respectively (See Figure 5.2.5) (Cranstone 1992). Slag from the ore hearth process was often re-smelted in slag hearths from the 17th century onwards (Bayley *et al*. 2001, 18).

By the late 1600s smelting experiments were being conducted with the cupola or reverberatory furnaces in Derbyshire and at Bristol. This process generally used coal as a fuel and the heat produced was allowed to flow across ore located in an adjacent chamber and not in direct contact with the fuel. The London Lead Company operated sites at Gadlys, Flintshire and Ryton near Newcastle upon Tyne (Willies 1993, 40). By 1701, a further cupola mill was operating at Marrick, Swaledale, North Yorkshire (Gill 2001, 147). Willies (1993, 40) describes a cupola furnace as '*a brick or stone built box, lined internally* *with refractory material, and supported against expansion effects either by iron strapping, or later, iron plates. The coal fire was placed at one end with an ash pit under. Flames from the fire passed over a low wall or fire-bridge, under the arched roof and over the hearth either to a tall chimney which provided the draught, or by a shorter or longer flue to such a chimney. The arched roof "reverberated" the heat down onto the ore/lead mixture in the hearth, which last took the form of a tilted saucer towards the front or smelters side of the furnace.*'

Figure 5.2.7 provides details of a reverberatory furnace. The reverberatory and ore hearth mills were of similar construction, only the furnace types differed in size. In the Northern Pennines the ore hearth smelt mills were usually sited close to or on the lead mine and usually had an adequate supply of water. Only the fuel had to be transported long distances to the mill. With the introduction of the reverberatory furnace, lead smelting became a major commercial activity. In North Wales the smelters were set up along the Dee Estuary where there was a ready supply of fuel from the Coal Measures and lead ore could be imported, and the lead exported, by sea (Williams 1986, 20).

5.2.2 Bale / bole furnace

The lack of reliable bale / bole excavations together with scant information on their detailed operations makes the interpretation of geophysical surveys from such sites difficult. A bale at Beeley, Derbyshire (Blanchard 1981) was excavated in 1967 and appears similar to Raistrick's (1928) bole, constructed from stone. However, the Swaledale surveys of Murphy and Baldwin (2001) have shown that in reality, certainly in Swaledale, bales constructed from stones are a rarity and sites consist of little more than slag spreads. Several of Murphy and Baldwins's sites will be considered in the following section, as their observations are just as valid as an excavation, due to the superficial and exposed nature of many of the sites where much of the archaeology is exposed.

5.2.2.1 Excavated examples

5.2.2.1.1 Beeley, Derbyshire

The Beeley bole was discovered in 1967 during the excavation of a triple cairn. Blanchard (1981, 72), summarizing the results, states that the bole probably dated from the mid-15th century. The simple bole measured 1.40m by 0.76m and was scooped out of the western side of the cairn. It contained a deposit made up of layers of slag and burnt wood about 0.15-0.20m thick. On the northwest side, away from the prevailing wind, there was a tap hole. Close by was a small piece of lead. Facing southwest there was a carefully constructed wind tunnel. The details from this excavation are shown in Figure 5.2.8.

5.2.2.1.2 Swaledale, North Yorkshire

Various researchers have examined the distribution of bole sites in Swaledale, North Yorkshire (Gill 1986; Barker 1978; Barker and White 1992). Murphy and Baldwin (2001; 2003) have provided the most in-depth study and have listed details of seventy bole sites. Although the identification of bole sites is not always easy, they state that the presence of pieces of metallic lead and / or a scatter of fire-reddened sandstone with spots or coatings of slag or lead is a visible identifier. In the Gunnerside Gill area, for example, they identified two sites using this method which both contained metallic lead.

Most boles were located on southwest facing scarp edges, to catch the prevailing wind, and the boles generally measure about 1.5m to 2.0m across. They were frequently hollowed out towards the centre and some had well defined openings towards the scarp edges. One peculiarity was that most boles were generally sited on sandstone. Boles were rarely found constructed on limestone (Murphy and Baldwin 2001). It is suggested the reason for this was the unsuitability of limestone as a base rock and construction material. Limestone cracks and decomposes on heating and may even form quicklime that would render recovery of the lead dangerous (Murphy and Baldwin 2001).

5.2.2.2 Geophysically surveyed examples

Galena is virtually magnetically inert. It is diamagnetic and has a mass magnetic susceptibility of 0.44 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 190) so any recordable geophysical contrast is likely to result from heat-altered material.

No upland bole sites have been geophysically surveyed specifically for this thesis. Hamilton (1998; 1999) has covered this aspect by surveying several sites in Swaledale (e.g. Grinton). One bole site (Vernon *et al*.1999a) at Dacre, North Yorkshire has provided interpretable geophysical data and the main structural elements of this site have been determined.

5.2.2.2.1 Grinton

Ground conditions: Rough moorland.

The first published geophysical survey of a bole-smelting site in England was recorded as recently as 1992, at Grinton, North Yorkshire (McDonnell *et al*. 1992). The site is one of a group initially identified by Barker (1978). Published work by Tyson and Spensley (1995) and Gill (2001) cover the Grinton area but do elaborate further on the boles.

Eight 1.0m resolution grids were surveyed with a fluxgate gradiometer (McDonnell *et al*. 1992). The results from this survey were inconclusive and it was unclear whether the survey was conducted over the site of a bole or slag furnace as both grey and black slag, were present. It was however suggested that furnace fragments might have generated some of the anomalies noted on the survey. A visit to the site in 1998 for sampling (Vernon *et al*. 1999a), confirmed the presence of two low-lying tips. The western tip was predominantly grey slag with furnace material whilst the eastern tip was composed of black slag that was generally spread about the site. A re-examination of the Grinton data has yielded very little additional information. It confirmed that spreads of lead slag have negligible magnetic properties. Most of the fluxgate gradiometer data falls between -4 and 4nT, the range of data frequently produced by non-fired archaeological targets. Two anomalies generated data between 15 and 30nT. It was considered that they could relate to disturbed furnaces or hearths. Another area on the eastern tip produced positive responses of 100nT generated by modern iron rich debris (Vernon *et al*. 1999a). Figure 5.2.9 provides details of the earlier survey (McDonnell *et al*. 1992; Vernon *et al*. 1999a).

Hamilton (1998) resurveyed and described the site in 1998. It is an area of approximately 1200m^2 and contains two mounds and several small areas of slag. The mounds consist of domestic refuse (north mound) and slag and charcoal (south mound). The slag was mainly yellow-coated, with cerussite ($PbCO_3$) formed from the decomposition of galena (Read 1962, 434-435). There was one isolated find of black vitreous slag.

Hamilton (1998) conducted both a 0.5m resolution fluxgate gradiometer and an earth resistance survey. The results from both surveys (Hamilton 1998) are shown in Figure 5.2.10. The fluxgate gradiometer survey identified an area of positive data about 7.0m in diameter, which Hamilton (1998) concluded was due to localized burning which may represent the remains of a burnt out shelter or store (Hamilton *et al*. 1999). The earth resistance survey identified an area of localized high resistance, probably caused by shallow stonework, visible on and immediately under the ground surface. Unfortunately it has not been possible to relate the 1992 and 1998 surveys precisely. Hamilton *et al*. (1999) do identify one possible bole on the survey.

5.2.2.2.2 Dacre, North Yorkshire

Ground conditions: Pasture.

Archival research identified Upper Nidderdale, North Yorkshire as an important centre for iron manufacture by the Cistercian abbeys of Byland and Fountains. After dissolution in 1539, much of these monastic lands came under the ownership of the Ingilby's of Ripley and the Yorke's of Bewerley. Both families were keen to exploit the natural resources of their Nidderdale estates (Blacker *et al*.1997).

Fieldwork in the vicinity of Smelt Maria Beck, near Dacre, North Yorkshire, which drains into the River Nidd at Summerbridge, has provided ample evidence for an established iron-working industry. Along the beck-side, several furnace sites have been discovered. In addition the presence of lead slag led to the discovery of a lead-smelting site adjacent to the beck, on the flood-plain of the River Nidd (Blacker *et al*. 1997).

Parch markings suggested that the smelt mill may have been a two-roomed building, typical of a 17th century smelt mill. However, both circumstantial and documentary evidence suggests that the site might be older (Blacker *et al*. 1997).

Smelt Maria Beck forms the southern boundary of the site. An artificial embankment has been constructed along the side of the beck, probably as a flood control measure. An exposure in the side of the beck reveals a layer of soil and silt underlain by a band of fine grey lead slag. Occasional larger pieces of slag were also evident.

A 0.5m resolution fluxgate gradiometer survey was conducted adjacent to the slag exposure in Smelt Maria Beck (Vernon 1997a). Most of the data fall between -5 and 5nT. Data outside this range are highlighted in the series of greyscale plots of the clipped data (Figure 5.2.11). Relief plots are used to emphasize identified anomalies (Figure 5.2.12).

Identifiable features are shown on Figure 5.2.13**.** A linear anomaly (Figure 5.2.13 - 1) curves across the south-east side of the survey adjacent to the beck. Initially it was thought that this represented a pipeline, but it has been expressed (G. Blacker, *pers. comm.*) that it might be material used to strengthen the embankment alongside the beck. A sub-circular area of mainly positive data, about 5m in diameter (Figure 5.2.13 - 2), is the most dominant anomaly and the recorded values are shown in Figure 5.2.14. The highest value in the survey (97nT) was recorded on the south side of it but most values are <15nT. Further, negative data are found in the central area of the anomaly. A linear anomaly (Figure 5.2.13 - 3) about 5 to 6m long runs south-eastwards from anomaly 2 towards Smelt Maria Beck, to an irregular area of positive values (Figure 5.2.13 - 4). The highest value associated with anomalies 3 and 4 are 58nT and 14nT respectively. The anomalies are interpreted as a sub-circular bole (2) with a channel (3) terminating at a slag dump (4) (Figure 5.2.13).

A small 0.25m resolution fluxgate gradiometer survey (Figure 5.2.15) over the sub-circular anomaly has confirmed the features previously identified and there is some indication in the form of weakly contrasting linear anomalies that suggest that the sub-circular feature may have been enclosed. The pattern of these anomalies approximates the area previously identified by parch marking (G. Blacker, *pers. comm.*).

A four-grid 0.5m earth resistance survey with a probe spacing of 0.5 m was conducted over the sub-circular anomaly. The results, however, were uninterpretable probably due to the underlying geology being close to the surface. This data is compared with the fluxgate gradiometer survey in Figure 5.2.16.

The Dacre bale is unusual as it is does not occupy a typical site on a scarp edge, it is on the flood plain of the River Nidd. The geophysical survey did not identify any indication of a water-powered operation so it is probable that air was introduced into the bale by hand or foot operated bellows. Although generally rare, valley bottom lead smelting sites employing bale and black oven technology occur in Teesdale, County Durham (Pickin 1992).

5.2.2.3 Discussion of the Bale / Bole

The small number of known bale sites suggests that they are ephemeral in nature. Although Raistrick (1928), Murphy and Baldwin (2001; 2003) and Timberlake (2003) record stone structures and burnt stone on bole sites, none of the bales geophysically surveyed to date conform with these observations. The surveys at Grinton and Calver Hill, Swaledale (Hamilton 1998; Hamilton *et al*. 1999) showed that bales were detectable as irregular areas of slightly enhanced positive data. Vernon *et al*. (2002) discussed that the response may depend on the original construction of the bole. As most boles were constructed on exposed hillsides, and that a bole was merely a circular wall containing a bonfire, it would not be unreasonable to suggest that boles could be constructed from any available suitable material, for example turf. Such material in time would erode in its exposed location leaving just a spread of slag. Murphy and Baldwin (2001) conclude that most bole sites have '*no associated pit or structure and little slag, indicating batch smelting of a small quantity of pure galena'*. The recent find by Timberlake (2003) provides evidence of both types of construction at one locality. The long tapping channel is not characteristic for all boles, but clearly exists in some situations. It is a feature that can be identified on fluxgate gradiometer surveys as for example at Dacre (Vernon 1997a). At Dacre the circular outline of the bale can also be identified as well as the slag spread. Consequently if there is a good state of preservation then there is every chance of being able to detect and interpret bales on geophysical surveys. A sub-circular heat affected area, which should offer some magnetic contrast, albeit possibly weak, with the surrounding material, would represent the location of the bole.

5.2.3 Ore hearth

The ore hearth has already been described (Chapter 5.2.1.1). Compared to some of the later techniques it was a simple process. Stratton and Trinder (1989, 24) describe the ore hearth as being built of either brick or stone. Refractory type material was not required as the process was confined to a small hearth. The principal components of the work area were made of cast iron. The ore hearth at the Keld Head mine smelter in Wensleydale, North Yorkshire, for example took the form of a box 58.5 cm. by 53 cm. and a depth of 30.5cm. The cast iron work-stone at the front of the hearth sloped down. Molten lead flowed down a groove in the work-stone and was caught in a cast iron sumpter pot. A hood over the hearth removed fumes. A tuyere was located at the rear of the hearth. Fuel was a combination of coal and peat. There was probably a fire put under the sumpter pot to keep the lead molten prior to it being ladled into an ingot mould. Clough (1962, 40) and Gill (2001, 30) reproduce one of the earliest known plans of a two hearth smelt mill dated 1735. In this example the hearths are 117cm wide with a depth of 84cm and the fumes are directed into a condensing chimney immediately above the hearth (Figure 5.2.17).

Ore hearths were common in many lead mining areas of the British Isles, often referred to as smelt mills, for example at Llanengan, Gwynedd (Bennett and Vernon 2002, 28) and Calbeck, Cumbria (Plan in the John Phillips Papers, Oxford University Museum of Natural History). In the latter example dated 1822, a fulling mill had been converted into a smelting mill and a short length of flue was constructed (Figure 5.2.18).

As the smelt mills evolved into large multi-hearth operation, long flues (often over one kilometre long) were essential to remove fumes and condense the lead. Eventually flues became a dominant feature of the North Pennine lead mining landscape and elsewhere, for example at Leadhills, Lanarkshire, Scotland (*personal observations*).

5.2.3.1 Excavated examples

Very few ore hearth mills have been excavated. Conservation and consolidation work by the Yorkshire Dales National Park Authority has been carried out in Swaledale, at Old Gang, Grinton and Blakethwaite smelt mills, requiring some excavation and recording (White 1992). Clough (1962), Raistrick (1975b), Bassham (1992) and Gill (2001) present details of the standing remains of ore hearth mills but only rarely has detailed excavations taken place. The Old Gang smelt mill was partly excavated by Cranstone (1992) and there are details of the ore hearth area.

5.2.3.1.1 Old Gang Mine, Swaledale, North Yorkshire

The Old Gang smelt mill is probably the finest example of a north Pennine ore hearth smelt mill. Cranstone (1992, 28) recognised that there is conflict between historical accounts of the site. The most recent work (Gill 2001, 91) takes advantage of archival accounts and the surveys completed by Cranstone (1992, 29). The Old Gang smelt mill underwent a number of modifications during its operating period that involved rebuilding the smelt mill and extending the flue system.

The first mill on the site, referred to as the New Mill, was constructed in 1797. It had two ore hearths, which the archaeological survey suggests vented into a central chimney (Gill 2001, 91). By 1829 a flue, about 700m long, had been constructed. Water was brought to the site and a roller crusher installed. The crusher might have been used to crush slag. An ore-roasting furnace was also constructed at this time. During the 1840s the New Mill was superseded by The Old Gang Mill, that measures c22m by c8.5m. A 7.3m diameter water wheel drove the bellows that supplied air for four ore hearths. Arches over the hearths that supported the hood for conducting the fumes away are missing but are a characteristic of other smelt mills in the area, for example Blakethwaite, Gunnerside (*personal observation*). During the 1940s an ore dressing plant was established in the mill and much of the interior was damaged. Cranstone (1992, 28 and 29) excavated the basal remains of one of the ore hearths down to floor level. The central part of the hearth had a flat stone base with a stone lined pit in front of it. The latter was interpreted as the site of the sumpter pot. The stones had been burnt *in situ* and the heat would have been from the fire used to keep the lead molten. At the side of the hearth base there is a further stone walled pit or tank that may have contained water. By putting hot slag in the water, the rapidly cooling slag became fractured or granulated and could be re-smelted without further treatment. Figure 5.2.19 shows the main component of the Old Gang site whilst Figure 5.2.20 is the excavation of the ore hearth.

5.2.3.2 Geophysically surveyed examples.

The geophysical survey at Grassington's Low Mill, North Yorkshire is believed to be the first survey ever to be conducted on an ore hearth smelt mill in Britain. There are no other known examples.

5.2.3.2.1 Grassington Low Mill, North Yorkshire.

Ground conditions: Rough pasture with a high drop down to the mill floor.

The Grassington Low Smelt Mill lies about 0.5kms south-east of Grassington village on the north bank of the River Wharfe (Roe *et al*. 1999). The mill was opened in 1605. Its location next to Brow Well, a major water resurgence, meant a constant supply of water all year round to turn the waterwheel. Originally, the mill had one ore hearth but in 1741, a second hearth was added. By 1755 a third hearth had been added, each hearth having one or a pair of chimneys immediately above it, which probably extended about 4m above the roof (Gill 1993,115 - 116). In the 1770s there was a reduction in the supply of ore and problems with fuel (peat). From October 1792, smelting was being transferred to the Cupola Mill on Grassington Moor. The last ore smelted at the Low Mill was 7th February 1793 (Gill 1993,116).

The geophysical survey was carried out to determine if any trace could be found of concealed features associated with smelting activity. For example, spread of slag deposits, buried structures, or the route of a water leat.

The site can be split in two: Undulating grazing land above the mill and the mill floor, with a 5m drop between them. The positions of the three hearths are discernible in the back wall of the mill. The mill is covered in rubble and domestic waste and a large tree grows out of the mill floor. South of the mill the ground slopes away to the River Wharfe. Several dumps of granulated slag are evident, one of which forms a small spit into the river.

A 0.5m resolution fluxgate gradiometer survey was conducted above the mill and on the mill floor (Vernon 1998a). Figure 3.2.21 show the layout of the site and the locations of the two surveys, repectively.

The fluxgate gradiometer data (Figure 5.2.22) north of the smelt mill contain numerous 'iron spikes' that do not form a uniform pattern. Several linear anomalies can be identified in the field. One anomaly trends north-east to south-west towards the north-east corners of the mill and may represent a water leat. There are possible linear anomalies on the mill floor. There are several clusters of positive data in the field that produce values up to 370nT. One cluster of positive data (maximum value of 67nT) adjacent to the river corresponds to the slag tip. A small 0.5m resolution earth resistance survey in the field above the mill provided little additional information (Figure 5.2.23). The anomaly identified as a leat on the fluxgate gradiometer survey was not discernible, possibly due to depth of burial. The interpretation of the data is shown on Figure 5.2.24 (Vernon 1998a; Roe *et al*. 1999, 125).

5.2.4 Cupola or reverberatory furnace

The reverberatory furnace was extensively employed at most major lead works by the 19th century, although the ore hearth process persisted in the Yorkshire Pennines. The process offered a greater output, continuous production and a consistent product. Despite their technology appeal very few examples of the furnace survived.

The technique was developed in North Wales and was first used on a large scale by the London Lead Company at Gadlys, Flintshire Lead Works and became the favoured smelting method of the many lead works on Deeside, Flintshire and elsewhere in Britain (e.g. Bristol) (Stratton and Trinder 1989, 26). The London Lead Company spread the technique into Derbyshire (Willies 1990, 5) where they totally replaced all the ore hearths (Gill 1993, 119) and other sites in the north of England (Stratton and Trinder 1989, 26).

The dimensions of the reverberatory furnace are greater than the ore hearth and so the mills tend to be larger. The continuous nature of the process also demands a constant supply of fuel and ore, therefore requiring storage areas (Willies 1992, 40).

There are very few surviving examples of reverberatory furnaces. One fine example exists at the Dyffryn Adda ochre works, Amlwch, Anglesey (Vernon 1996, 44). It is built from refractory bricks bound together by iron straps. Willies (1992, 41) considered what components of reverberatory lead smelting might survive and suggested that any metal may have been removed for re-use elsewhere. Foundations would have to be fairly massive to support the weight of the furnace. There might be an ash pit at one end and even vaulting beneath the furnace to stop water penetration, and the refractory material used for furnace construction would probably differ from surrounding building materials. Other indications of a reverberatory furnace site might be a location next to water and a tall chimney close by, possibly with a short flue. Longer flues, for draw, tend to be associated with slag hearths often used in conjunction with the reverberatory technique.

5.2.4.1 Excavated example

There are very few examples of excavated reverberatory mills and even these sites do not have any intact furnaces. The Grassington Cupola Mill contains many of the features associated with a reverberatory operation (Gill 1993, 122). The smaller Hafna Smelt Mill, Gwynedd provides an example of a small-scale smelting operation (Bennett and Vernon 1990, 66).

5.2.4.1.1 Grassington Cupola Mill

The Grassington Cupola Mill, North Yorkshire was built in 1792 to replace the Grassington Low Mill. The reverberatory furnaces were constructed in 1793 (Bassham 1992, 37). Clough (1962, 77) notes that the last pig of lead was stored in the mill in 1885 although it probably ceased operating in 1882 (Gill 1993, 122).

There are two published surveys of the mill, one by Clough (1962, 77) drawn in 1947 and the other in 1992 by Bassham (1992, 38). Gill (1993, 118) describes the mill and its operations. The Cupola mill incorporated an earlier water powered ore hearth mill (The Moor Mill – built in the 1850s) that was converted to a slag hearth. There is a substantial flue system with chimney, complete with condensing chambers that extends across Grassington Moor for a total length of 1.8 km. The direct route from the flue to the chimney is 520m but by inserting flagstone dampers, fumes can be diverted through secondary loops and through condensers (Gill 1993, 121). There are substantial differences between the two surveys of the mill. The Clough survey (1962, 77) identifies the main components of the mill whilst the Bassham survey (1992, 38) is an accurate survey of the outer walls. Gill (1993, 124) has produced scale drawings of the furnaces based on contemporary accounts. Figure 5.2.25 places the information from the Clough survey on to the Bassham survey, with Gill's furnaces superimposed to illustrate the relative space that the furnaces would have occupied. One interesting feature is that the furnaces were not located on the back wall of the mill, in contrast to the ore hearth process.

5.2.4.1.2 Hafna Mill

The Hafna smelt mill in the Gwydyr Forest, Gwynedd is a rare example of a smelt mill on a Welsh mine site. Most Welsh lead ore was transported to either Deeside or Llanelli. The smelt house is described as having furnaces (rather than a hearth) for smelting both lead and zinc (Bennett and Vernon 1990, 66). There is sufficient circumstantial evidence to fulfil most of the criteria assigned by Willies (1992, 41) for a reverberatory furnace to have existed in the mill.

The mill was originally surveyed in1989 (Bennett and Vernon 1990, Figure 21 facing page 80) and was excavated and surveyed by the Gwynedd Archaeological Trust for a land reclamation and mine site conservation scheme, before becoming a scheduled monument. The mill floor was cleared of debris during the excavation to reveal large areas of brickwork, some refractory and a short length of railway, presumably to move ingots. There are two low flue arches (one bricked up) in the back wall leading to a short length of flue and a tall chimney. In front of the smelt mill there is a large pond which was probably used for collecting slimes from the adjacent ore processing mill but could equally have been used for granulating slag. There is a notable absence of slag around the smelt mill. Adjacent to the open flue arch there is a circular elevated pit constructed from brick, purpose unknown. Immediately north of the mill there is a small engine house that housed blowing machinery with the tuyere piping still *in situ*. This machinery is apparently inconsistent with reverberatory furnaces, but may have been required for ancillary processes.

5.2.4.2 Geophysically surveyed examples

Several reverberatory furnace sites were inspected for the current research including Grassington and Hafna. The site of the Gadlys smelter, Flintshire was cleared by the London Lead Company on its closure (C. Williams, *pers. comm.)* Much of it is now under sheep grazing land with the occasional hillock composed of brick and slag. However, it was only possible to geophysically survey the Marrick Cupola mill, the first reverberatory mill in Yorkshire (Gill 2001, 147).

5.2.4.2.1 Marrick cupola mill, Swaledale, North Yorkshire

Ground conditions: Moorland with a short drop down to the mill floor.

The Marrick Cupola Smelt Mill lies about 2.0kms west of Reeth village on the north side of Swaledale. Construction of the mill commenced in late 1700 and was in operation the following year. It was used as a 'jobbing' mill, smelting ore from surrounding mines including the Hurst and Grinton mines to the north and south, respectively, and from the Buckden Gavel mine in upper Wharfedale. In the earliest correspondence on the mill in 1700 it is referred to as the Cupuloe (*sic*) (Tyson 1989, 26). By 1723, the Cupola Mill was in a ruinous state and the equipment, stone and timber were being sold off (Gill 2001, 146 - 147).

The site can be split in two. The hillside above the mill consists of rough grazing land that rises steeply from the backwall of the mill, and the mill floor 2m below, with tip material along its frontage. The mill floor (32.0m long by 9.0m wide) is covered by rubble interspersed with linear hummocks that may represent the locations of internal and external walls. On the east side, the tipped area slopes away from a flat ledge 2.0m to 5.0m wide. The tip consists of material excavated out of the hillside to form the mill floor, and black slag from the smelting process. Figure 5.2.26 shows the mill structures together with the surrounding topography.

The geophysical surveys were carried out to try and identify two possible flues and any remaining structures on the mill floor (Vernon 2000b). The first flue was identified as a linear strip of bare ground running up the hillside and the second as two sections of vertical masonary (Lamb 1992). In the back wall a shallow linear depression has also been identified trending up the hillside. These features are identified on Figure 5.2.26.

A 0.5m resolution fluxgate gradiometer survey consisting of eight 10m grids was conducted over the steep ground above the mill, and a further eight grids on and in front of the mill floor (Figure 5.2.27). The ground north of the smelt mill contains several linear positive anomalies trending up the hill side. The area immediately around and within the smelt mill also contains various clusters of positive data, most of which cannot be attributed to specific features and are probably generated by iron debris. There are however two particular clusters of positive data (>100nT) which may be significant. One lies against the back wall of the mill and the other adjacent to an obvious entrance in the front wall of the mill. The ranges of data recorded for each grid are shown in Figure 5.2.27. It can be seen from the table that grids that occupy the smelt mill floor and frontage (grids 9 to 16) have a greater data range than those on the hillside (grids 1 to 8) (Vernon 2000b).

Figure 5.2.28 shows the data clipped to various ranges. The positive linear anomalies previously commented on, which run away from the mill up the hillside, can clearly be identified on all the data between -30nT to 30nT. The area of bare ground on the hillside above and at the southern end of the mill produces lower values. It is presumed that the exposed subsoil contains a lower concentration of iron (with the potential to exist in a magnetic form) than the overlying topsoil which covers the remainder of the hillside. Elsewhere on the survey a number of other weak linear anomalies have been identified (Vernon 2000b).

Identifiable anomalies are shown on Figure 5.2.29. Anomalies a and b (Figure 5.2.29 - a) and (Figure 5.2.29 - b) are two linear belts of positive data trending approximately northwest / southeast and approximately west-north-west / east-south-east, respectively up the hillside. It is suggested that they represent the positions of flues. In other local examples of mills, Old Gang, Surrender and Grinton the flues terminate at chimneys (Raistrick 1975b, 75 - Map 6, 46). There is no additional evidence to suggest that the flues found in this survey also terminated at chimneys. Most of the positive data that make up the anomalies are less than 20nT. Anomaly (c) is the division between low value data (less than 3nT) and the slightly higher mean value (5nT to 6nT) of the remaining hillside. It is thought that this is the junction between the exposed sub-soil and vegetation covered ground (north side). The survey conditions were very difficult, the ground was very slippery in this area and it was not always possible to hold the magnetometer at a constant distance above the ground. Anomaly g (Figure 5.2.29 - g) is a cluster of positive data with a maximum value of 119nT along the backwall of the mill. Anomaly h (Figure 5.2.29 - h) is a cluster of positive data with a maximum value of 82nT. Other anomalies in the interior of the mill with high values up to 423nT are not possible to interprete (Vernon, 2000b).

An earth resistance 0.5m resolution survey was conducted on the hillside above the mill (Figure 5.2.30). Figure 5.2.31 (a to l) shows the earth resistance data clipped to various ranges. The west side of the survey produces low earth resistance data and roughly corresponds to an area which is predominently bare ground. The east side of the survey is predominently high data which corresponds approximately to a vegetated area. It is suggested that the contrast is produced by the free draining and therefore drier ground conditions that occur on the eastern side of the survey. On the western side of the survey the mobile probes would have been placed in the moist sub-soil. Despite this variation the earth resistance survey does achieve its objective and confirms the presence of the two linear anomalies (the flues) that trend northwest from the mill (Vernon 2000b).

The western anomaly is a poorly contrasting feature and begins to show some contrast when the data are clipped between 50 and 250 ohms. At the northern end of this anomaly there is a cluster of high earth resistance data that produces values above 500 ohms. This might indicate a structure at the northwestern end of the linear anomaly. The data also suggests that the linear anomaly may extend beyond this cluster but this is not supported by the fluxgate gradiometer data. Figure 5.2.31(l) shows the two grids that cover the western linear anomaly. The eastern anomaly is clearly defined in the data. It is essentially an area of low earth resistance data (Figure 5.2.31(g)) surrounding a higher earth resistance linear anomaly. (Vernon 2000b).

A two grid 0.5m resolution magnetic susceptibility survey was conducted over the slope above the mill (Figure 5.2.32 (a to f)). Most of the high data lie on the west side of the survey on exposed sub-soil. The linear anomalies noted on both the earth resistance and fluxgate gradiometer data are not discernible. However several poorly contrasting linear anomalies can be identified which did not appear on previous surveys. It is probable that they represent very superficial features on the surface which may not be related to smelting operations (Vernon 2000b).

In interpretation of the surveys is shown on Figure 5.2.33. Photographs of the survey are included in Figure 3.2.34 to show the extent of the mill floor and the difficulties encountered.

5.3 Copper

5.3.1 Introduction

The common forms of copper ores found in Britain are chalcopyrite ($CuFeS_2$), calcocite (Cu_2S) and malachite ($Cu_2CO_3(OH)_2$) (Bayley *et al*. 2001, 15). Copper deposits are generally located on the west side of the British Isles, for example, Loch Fyne area of Scotland, Cumbria, northwest and central Wales and Cornwall / Devon. Several unrelated deposits occur peripheral to the Pennines at Alderley Edge (Cheshire), Ecton (Staffordshire) and Middleton Tyas (North Yorkshire) (Dunham *et al*. 1978). Copper smelters were mainly confined to Cornwall, Devon and South Wales. Several others existed on Anglesey (Parys Mountain), Cumbria (Coniston), Middleton Tyas and Ellastone (Ecton). All these smelting sites are post-medieval. Earlier sites are unrecorded or their locations are not known although a potential site has been located on the Great Orme, Llandudno, Aberconwy (Hammond, Great Orme Mines, *pers. comm.*).

5.3.1.1 Smelting Techniques.

Chalcopyrite ($CuFeS_2$) is probably the most common copper ore in Britain. Tylecote (1984) indicates that copper smelting was conducted in several steps. The ore was first roasted to burn off sulphur. This took place in several stages (Smith 1994, 117) with the intention of converting the iron sulphide to an oxide that was slagged with lime and silica, derived from mixed gangue material. Copper matte was tapped from the furnace. The slag and the matte form two distinct layers and are separated after tapping. The resulting copper matte was then broken up and re-roasted and re-smelted on a number of occasions. Eventually a final smelt would produce a flow of molten copper (melting point 1084ºC (Tylecote 1984, 128)).

Early smelting sites are not known or have not been recognized in Britain, although there is ample evidence for widespread Bronze Age copper mining (Timberlake 2001). If sites are found it is probable that they would be similar to early lead smelting sites, consisting of a smelting hollow scooped out in a surface (Tylecote 1984, 6). A cylindrical shaft type furnace had evolved by the Chalcolithic period, and such sites are known in the Pyrites Belt of southwestern Iberia (Anon 2001). The archaeology of the Mount Gabriel bronze mines in southern Ireland is well documented (O'Brien 1994). However, no evidence has been found there to indicate the location of copper smelting activity. O'Brien (1994, 187) argues that the spread of copper finds, for example copper ingots on the Mizen Peninsula, southwest Ireland, would suggest that the copper was smelted locally rather than being transported to a central smelting area. Finds of crucible fragments and moulds away from copper mining areas may suggest that the copper was refined elsewhere (O'Brien 1994, 187). The survival of primary copper smelting furnaces has been questioned using the argument that small bowl furnaces may have been broken up after each smelt (O'Brien 1994, 186). Even under the latter circumstances it is probable that a magnetic signature from a furnace would remain and be detectable by geophysical prospection. High temperatures would be required for smelting copper and this process would have readily produced magnetic forms of iron oxide.

On the Great Orme, North Wales, it is speculated that ore might have been moved to the forested coastal areas for smelting (Roberts (Great Orme Mines), *pers. comm.*), although after an extensive search one copper-smelting site has been detected on the Great Orme (Hammond (Great Orme Mines), *pers. comm.*). Spreads of copper slag have been found at a few locations along the north Wales coast. Most appear to have no archaeological context and it is suggested that the slag could have been quite easily been brought in as ship ballast. One deposit at Llandudno however is about 100m broad and extends for 1km along the beach. At one time this beach area must have been dry land, as the remnants of *in situ* tree trunks are evident. Roman coins and a palstave have also been found there (Smith 1993).

Early copper smelting sites have been studied extensively in both Israel and Spain (Rothenberg 1972; Rothenberg and Blanco-Freijeiro, 1981). At Timna, Israel (Rothenberg 1972, 74) a number of copper smelting furnaces have been excavated, dating from the Ramesside period (Late Bronze Age – Early Iron Age). One copper smelting area measured 10.0m by 6.0m with a slag tip up to 50cm thick. One stone built furnace was constructed in a hollow measuring 1.0m by 2.0m. The smelting bowl was 40cm deep by 45cm in diameter. A further pit was located in front of the furnace and like the furnace was burnt. Evidence was also found that slag had actually solidified outside the furnace. Molten copper was removed via a tapping hole. Figure 5.3.1 shows a plan and section of the furnace.

Rothenberg and Blanco-Freijeiro (1981, 45) have excavated predominantly Roman copper smelting sites in the Rio Tinto area, Huelva, Spain and described one probable furnace as a hard-burned area about 40cm in diameter with a slagged stone in front of it. Surrounding stones with traces of a slag coating probably were from the furnace shaft.

Shaft type furnaces were probably used to smelt copper through the medieval period in Britain although evidence is scant and Tylecote (1984, 69 - 75) draws on continental Europe for his examples. Hughes (2000, 19) comments that '*up to the 16th century the* *technology that had been in use for copper smelting was derived from Roman technology current for at least 1500 years*'…. '*and were adaptations of the small Roman shaft furnace*'.

Waterpower was probably applied to British copper smelting sometime in the 16th century. Certainly in Cumbria the copper mining revival, associated with a partnership of English and German capitalists, brought in new technology to the area. By 1574 coppersmiths had arrived in Keswick, Cumbria and a large water-powered hammer was under construction (Bridge 1994, 108). Smith (1994, 119) provides details of the eight furnaces employed in the 16th century Keswick copper works. In 1580, they were arranged in two sets of three and blown by water-powered bellows. Only two furnaces in each set were operating. The remaining two furnaces were located in the same area as the refining furnace. The smelting furnaces consisted of iron pans that supported a clay lining mixed with charcoal. There were problems with this method requiring the various tapping holes to be cleaned out regularly. Slag was removed by lifting it off as a crust from a fore-hearth prior to tapping the molten metal.

By the mid-1700s reverberatory furnaces were becoming common. In 1797 Parys Mountain, Anglesey, for example had two smelting houses at Amlwch, Anglesey for the Mona and Parys Companies. They housed thirty-one reverberatory furnaces with chimneys up to 12.4m high (Hope 1994, 47). Michael Faraday, the eminent physicist, visited Amlwch in 1819 and described the refineries (smelters)… '*These consisted of rows of reverberatories exactly similar to those used at the Swansea works in which the metal is roasted over and over again. The ore does not come in a crude state to them but is first* *roasted up on the mountains in kilns by which a great part of the sulphur is separated and then it comes to these works. The metal is not tapped into water here as in Swansea but runs into pigs*' (Tomos 1971, 77).

At Parys Mountain, the roasting of the predominantly chalcopyritic ore was done next to the mine. There were several stages to the roasting processes. The first involved placing heaps of ore on a bonfire in the open. This would ignite the sulphur and would continue until all the sulphur was burnt off. Eventually this process was controlled in kilns, constructed from local stone with iron grates. The fuel was probably a mixture of gorse bushes and peat. The temperature within the kilns would have to exceed 248ºC for the sulphur to ignite (Hope 1994, 37). Ore roasting areas can be identified by concentrations of burnt rock still visible around the copper mine opencast pits (*personal observation*).

At the Middleton Tyas Copper Mine, reverberatory furnaces were also used to smelt the copper ore and were similar in design to those used for lead smelting (Figure 5.2.7). Hornshaw (1975, 141 - 142) provides a translation of Gabriel Jars (a Swedish Industrialist) account of a visit to the smelt works in 1781 and this is summarized as follows. '*The smelting furnace is a reverberatory type with one door opposite the hearth (under the chimney). The tapping hole is in the middle. The furnace and hearth are built of fire resistant sandstone, the joints sealed with clay. It is built on a mass of masonry, not a vault, and although this takes longer to heat up, it retains its heat longer. Its floor needs to be repaired once every two months and replaced every six months. When the furnace has been stoked for several hours it is charged through a door under the chimney with a mixture of various kinds of ore, the copper matte from previous tappings, crushed coal and slag. Slag* *floating on the surface of the resulting molten mass is removed by running it into rectangular cast-iron moulds mounted on wheels.'*

Eventually 90% of Britain's copper smelting capacity was located within a 20 miles radius of Swansea, South Wales utilizing a system of reverberatory furnaces for repeatedly roasting the copper ore, a system that became known as 'The Welsh Method' (Hughes 2000, 16).

5.3.2 Simple furnaces

No examples of copper smelting shaft furnaces have been excavated in Britain. Those excavated in Continental Europe and the Middle East suggest that the shaft has an internal diameter less than 0.50m and is constructed from clay or a stone/clay mix similar to an iron smelting shaft furnace. Plano-convex ingots of copper have been found in Cornwall dating from the Bronze Age and metallographic examination indicates they were formed in the base of a furnace, rather than the copper being tapped into an adjacent pit (Tylecote 1984, 30 - 31). North (1962, 20) reports similar copper 'cakes' found on Anglesey, about 0.30m in diameter and 0.06m thick and stamped with a Roman inscription. It is not clear if they were also formed *in situ* in a furnace, although North suggested that they were made in a circular mould.

5.3.3 Roasting and ore hearths

There are no known examples of pre-medieval roasting hearths, however the high sulphur content of the pyritic ores would make this process relatively simple to roast in the open-air. Pyritic ore will also spontaneously combust under the correct oxidising conditions

(Sinnatt and Simpkin 1922, 28). On Parys Mountain it was common practice to burn the ore. The earliest method involved burning the ore on small bonfires and eventually in specially constructed rectangular kilns (Hope 1994, 34 - 43). At Rio Tinto and elsewhere on the Spanish Pyrite Belt the pyritic ore was burnt in regularly spaced heaps out in the open. These heaps or *teleras* contained 200 tons of pyritic ore and used 14 tons of brushwood to set it alight (Avery 1974,114 - 115).

5.3.3.1 Geophysically surveyed examples

Chalcopyrite is paramagnetic and has a mass magnetic susceptibility of 0.55 to 10 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 191). The combination of high temperatures and the presence of iron in the ore are two significant factors that should contribute the development of strong magnetic signatures on copper smelting sites. The following two examples are believed to represent the only two geophysical surveys carried out on copper smelting sites in Britain.

5.3.3.1.1 Whashton, near Richmond, North Yorkshire

Ground conditions: Heavily vegetated area of tall nettle beds with a few open spaces.

Copper mining in the vicinity of Richmond, North Yorkshire was first mentioned in 1454 (Raistick 1975a, 109). The Whashton copper smelt mill lies adjacent to Coppermill Bridge next to Smelt Mill Beck. Raistrick (1975a, 110) comments that there is no building to be seen but extensive slag tips radiate from a flat area of land. It is possible that the site dates from the early to late 1600s. In contrast, Hornshaw (1975, 108) mentions that '*close to the beck is the outline a small rectangular building some 20ft by 12, which could be the mill.*' The primary copper ore was chalcopyrite (Dunham and Wilson 1985, 157) but malachite and blebs of copper are also found in the slag (Raistrick 1975a, 110).

When geophysically surveyed the site heavily overgrown with clumps of gorse bushes and high nettles. Nevertheless it was possible to identify the outline of the building described by Hornshaw (1975,108) with the short side aligned approximately 45º to the beck. A 1.0 resolution reconnaissance fluxgate gradiometer survey consisting of six part-grids was conducted over the slag tip and mill. The survey is shown in Figure 5.3.2. The outline of a rectangular anomaly can be identified with positive values as high as 189nT. Over the area of slag the highest value was 135nT. The rectangular anomaly would correspond to the mill building with the high values possibly associated with the location of furnaces.

An attempt was made to conduct an earth resistance survey but this was virtually impossible due to the overgrown nature of the site. High earth resistance values were common over the slag dump. The site has not been revisited to conduct surveys at higher resolutions.

5.3.3.1.2 Ellastone, near Ashbourne, Staffordshire

Ground conditions: Rough pasture.

The village of Ellastone lies about 7 kilometres south-west of Ashbourne, Staffordshire. The copper smelter is located close to the River Dove and it smelted the ore from the Ecton copper mines about 15km to the north.

During the medieval period much of the land around Ellastone was controlled by the Augustinian Order at Calwich Abbey, located one kilometre northeast of the village. The Augustinians probably constructed a fishpond between the Abbey and the River Dove. A leat, known locally as ‘Hammer Ditch’, runs west from the pond to join a small reservoir in Ellastone village. A stream runs south from this reservoir to the River Dove and forms the eastern boundary of the survey area.

On dissolution of the Abbey in the 1530s, it is believed the land was given to the Fleetwood / Dunscombe family who took up residence at a house on the site of the Abbey. The Ellastone copper smelting mill was built or possibly modified from an existing building in 1660 / 61 (Robey and Porter 1972, 67). The Ecton Copper Company paid an annual rent of £25 for the copper mill, which was probably paid to Sir Richard Fleetwood. Together with the Duke of Devonshire, Fleetwood was a co-partner in the Ecton Mines. Both mine and mill were operating in 1665. However by 1686 a survey of the area reported that both had closed. The site of the mill was known as ‘Copper Mill Yard’ (Robey and Porter 1972, 67).

A survey of the Calwich Abbey Estate c1740 in the Lichfield Record Office, Staffordshire (W.Taylor *pers. comm.*) shows the ‘*Copper Mill*’ on the west side of the stream that runs southward from Ellastone to the River Dove (Figure 5.3.3(a)). On the east side of the the stream the land is identified as the ‘*Copper Roasting Piece*’. The 1847 Tithe Map (Figure 5.3.3(b)) of the same area shows a leat running through the area of the Copper Mills. The leat can still be identified in the field south of the survey area as a linear ditch. The first edition 25 inch ordnance survey map published in 1880 (Figure 5.3.3(c)) makes no reference to either the leat or the ‘*Copper Mill*’. One feature common to all three maps is a building on the north side of the field against the road. This building does not exist now, its position is roughly on the line of the farm track that forms the northern boundary of the survey area.

The site of the smelter is now used for rough grazing and is still known as '*Copper Mill Field'* (Porter and Robey 2000, 249). Much of the field is hummocky with occasional shallow gulleys generally trending towards the stream. An obvious shallow terrace runs parallel with the stream.

Animal activity has revealed the underlying soil. Dark grey soil occurs in a distinct area on the north-west side of the field with occasional fragments of slag and pieces of coal. One large fragment of black glassy slag with green-blue copper staining was found. Several pieces of tap slag were also found in the stream. A distinct copper-rich slag layer was noted in the eastern bank and large masonary blocks and other walling were noted in the west bank of the stream, in the southern part of the survey area.

A fluxgate gradiometer survey at 1.0m resolution was conducted over the '*Copper Mill Field'* (Vernon 1997b). Figure 5.3.4 shows the grid and the geography of the site and Figure 5.3.5 fits the survey to the site. Most of the data fall well within the -10 to 10nT range. In Figure 5.3.6 (a to i) the data has been clipped to various ranges. In the centre of the survey there is a prominent positive anomaly with the white halo around (maximum value of 723nT). It is believed to be a vertical metal object in the ground (A. Schmidt, *pers. comm.)*. A prominent linear anomaly runs across the north-west corner of the survey. The alternating positive and negative values is a typical pattern produced by metal pipelines but it has been reported that there is no known pipeline at this location (Bill Stretton, *pers. comm*.). An alternative explanation for this feature is that it may represent a concentration of iron-rich material along an old field boundary. At a range of -25nT to 25nT (Figure 5.3.6 (c)) several other linear features also become evident.

Two areas stand out as being magnetically ‘noisy’. One in the north of the survey the other in the extreme south. The scattered nature of the northern data would suggest that this results from domestic occupation. There was once a building just to the north of this area, so much of the noise could be generated from iron in the domestic waste, especially if the building was, for example, used for blacksmithing. The uniformity and clustering of the southern area of “noisy” data would suggest that it is also related to a specific activity as this area does contain concentrations of slag. The overall response falls between -50nT to 50nT. Another anomaly with a grouping of uniform positive responses (maximum 59nT) lies immediately to the east and might, based on its dimensions, may be the location of the furnace. At the northern end of the survey, there are several linear anomalies that may represent slag filled ditches. Many other linear features start to become more pronounced between -5nT and 5nT at the southern end of the survey.

One significant point is that the southern slag tip and surrounding area produced a lower background reading than the area to the north. The line of transition appears to partly coincide with a boundary shown on the 1880 ordnance survey map (Figure 5.3.3(c)) and may delineate the devision between farming and smelting activities.

The 0.5m resolution fluxgate gradiometer survey is confined to the southern portion of the field and Figure 5.3.7 (a to f) shows the data clipped to various ranges and it is possible to see linear anomalies running approximately northwest / southeast across the survey. Other minor linear anomalies appear to run at right angles to them. Unfortunately at the lower clipping ranges, the negative response produced by the adjacent iron fence tends to mask many of these features. It is possible in Figure 5.3.7 (d and f) to see that the elongated area of positive data, previously thought to be a furnace location, is partially surrounded by linear features, one of which may represent a ditch. Another pronounced linear anomaly runs roughly northeast-southwest and follows the river bank.

A 0.5m resolution earth resistance survey was also conducted over the southern portion of the site. The spacing of the mobile probes was 0.5m. Figure 5.3.8 is the 0.5m resolution earth resistance data positioned on the grid. It covers much of the southern part of the 20m fluxgate gradiometer grid. Figure 5.3.9 (a to e) shows the data clipped to various ranges. Three main areas can be identified by the data. The first occupies much of the western and northern side of the survey. It is typified by low earth resistance data (< 35 ohms) and corresponds to an area of low-lying ground. On the eastern side of the survey, the second area, a sinuous belt of high resistance data runs sub-parallel to the stream. Values are in excess of 70 ohms. The third area is defined as a central block with values between 35 and 70 ohms. There are several linear anomalies within it, which are poorly contrasting. One linear feature runs across area one into the central area from the north-west. This feature may be connected with other features on this trend noted on the fluxgate gradiometer survey. The probable slag tip also shows up as an area of higher resistance.

A magnetic susceptibility survey at 0.5m resolution over the southern half of the site (Figure 5.3.10) did not detect the slag dump. Data fall between 5 and 100 x 10^{-5} SI Units, which is relatively low for a smelting site. Two linear anomalies were identified, one trending northeast / southwest on what could be the western side of the smelter. The other, a weaker anomaly, trends northwest / southeast on the northern side of the smelter. A cluster of higher values may identify the location of the furnace. It is possible that many of the features previously identified are too deep to be detected by the magnetic susceptibility instrument.

The interpretation of the Ellastone site is shown on Figure 5.3.11.

5.4 Tin

5.4.1 Introduction

The tin smelting industry in Britain is confined to southwest England. The principal ore is cassiterite (SnO_2). It is paramagnetic and has a mass magnetic susceptibility of 16 x 10^{-8} m^3/kg (Hunt *et al*. 1995, 190). A temperature of at least 1150ºC is needed to smelt the cassiterite (Gerrard 2000, 129), although tin itself has a melting point of 232ºC (Tylecote 1990, 43). In the medieval period smelting was conducted in a shaft furnace. In Cornwall they were constructed from granite blocks that were internally lined with clay (Gerrard 2000, 129 to130).

From the 1600s onwards, the tin (and copper) mining history of Cornwall and Devon is probably the most researched in the Britain. Most of the historical accounts cover the period from the mid 18th century through to the industry's decline in the 20th century (Hamilton Jenkins 1962; Noall 1973, 1983; Barton 1978,1989). Little is known about the early history although various manuscripts give glimpses of medieval activity. Several researchers have tried to produce overviews (Hamilton Jenkin 1962; Barton 1989) whilst Gerrard (2000) and Greaves (1981, 1984) have concentrated on the tin-streaming (a form of alluvial mining) industry in Cornwall and Devon, respectively, and placed them in their archaeological setting. Overall the early history of tin smelting is poorly documented and similarly to tin mining history, most accounts refer to post-medieval activity.

5.4.1.1 Smelting Techniques

Tin slag is the main evidence for early tin smelting and as experiments have shown it is not necessarily produced in large quantities (Craddock and Craddock 1996, 61). Finds of tin slag in an archaeological context are rare. The oldest known slag in Cornwall is from an Early Bronze Age site at Caerloggas near St. Austell (Tylecote 1990, 42; Salter 1997). Hunt (1887, 16-17), referring to Cornwall, comments that, '*tin was usually purified* (smelted) *by digging a hole in the ground and throw the tin ore on a charcoal fire, which was probably excited by a bellows'*. He goes on, '*many such rude pits containing smelted tin, have been discovered in this district, and are called 'Jew's Houses'*.' The accuracy of the description has yet to be verified as early tin smelting furnaces have yet to be found, if the sites could be identified again. There is no doubt that they would have been similar to other methods of smelting in common use at the time, probably employing a type of small shaft furnace. Excavations of the Iron Age hill fort at Chûn near St.Just, Cornwall in 1925 revealed a furnace that was assumed to be for smelting tin. Charcoal and slag were found in the furnace and a lump of metallic slag or dross was found in an adjacent building (Leeds 1927, 218; Hamilton Jenkin 1962, 28; Tylecote 1990, 44).

Information though on tin smelting from the Iron Age through to the medieval period is scant. There is no reliable information that identifies Roman tin mining and smelting sites and evidence for activity in this period consists of cakes of tin inscribed in Latin, or finds of Roman coins (Gerrard 2000, 22).

The granting of Royal Charters to form the Stannaries amounted to standardization within the tin industry. The earliest Charter dated 1201 confirmed the previously accepted practices of the 'tinner' with the privileges to '*…digging tin and turfs* (peat?) *for smelting it…….and of buying faggots to smelt the tin, without waste of forest…*' (Hamilton Jenkin 1962, 28). Hamiton Jenkin (1962, 68) also remarks that early tin smelting was carried out next to the tin deposits but does not confirm if the tin referred to was from a mined or alluvial source. Bellows provided a blast of air within the furnace and tin would either collect at the base of the furnace or be tapped at the front. Gowland (1899, 32) and Le Grice (1846) describe a furnace, at Trereife, Cornwall, as an inverted cone, 91cm in diameter and 91cm deep with sides of hard clay, built into a bank of clay. The base was a flat stone about 30cm in diameter edged with small stones. It was presumed that air was introduced with bellows, through the tap hole.

Although documentary evidence is scant it has been suggested that water-powered blowing houses were probably in general use by the mid-14th century (Malham *et al*. 2002). The houses were usually a crude structure built of stone and turf with a thatched roof. The furnace was typically constructed from blocks of stone, usually granite, clamped together with iron banding. It is unclear if the furnace was lined with clay (Malham and McDonnell, 2003) or whether the stone blocks were jointed closely together. Layers of tin ore and charcoal were placed in the furnace and ignited, and an air blast provided by water-powered bellows. Molten tin flowed from the front of the furnace into a stone trough or 'float'. It was then ladled into a heated iron pot of about 90cm diameter, where it was kept in a molten state. By plunging water-soaked charcoal into this pot, it was possible to agitate any remaining slag to the top and skim it off (Hamilton Jenkin 1962, 68).

The reverberatory smelting technique was introduced into Cornwall in about 1702 (Smith 1996, 93). For a period of time blowing house and reverberatory technology operated simultaneously but as tin-streaming declined the number of blowing houses decreased (Barton 1989, 20 - 21).

Smith (1996, 91) details some of the problems associated with efficient tin smelting. The slag from blowing houses might contain 15% tin whilst that from a modern two-stage smelter is only about 2%. About 1704 a technique was developed whereby cast iron was mixed with tin ore that typically contains silicates, for example quartz. The addition of iron tended to displace tin from the slag and reduced tin losses. The resulting slag was predominantly silicate with the iron combining with the tin to form re-smeltable dross that could contain up to 15% iron (Smith 1996, 94).

Despite the introduction of the reverberatory furnace the shaft furnace was still in use in Europe in the late 19th century. At Altenberg in the German Erzgebirge a shaft furnace was used alongside a reverberatory furnace, the latter used for roasting the ore. Charlton (1884, 76) describes the shaft as being, '*7 feet high and measures 12 inches in breadth and 18 inches in the front…....the tap hole is 2 inches square and discharges into a square stone sump…….out of which the metal is ladled into moulds*'. The process is not unlike the method used in southwest England blowing houses although it is unclear from the description whether the water-powered technology used in the ore-dressing process was also used to power the bellows.

5.4.2 Simple tin-smelting furnace

Gerrard (2000, 19 - 21) states that the simple tin-smelting furnace consisted of, '*a pit dug into the ground, to receive the molten metal, whilst a flimsy superstructure of stone and/or clay would have formed the furnace itself. A mixture of black tin and charcoal would have been placed in the furnace and then burnt to release the molten metal into the bowl*'.

Evidence from shaft furnace excavations in general, particularly for iron smelting (e.g. Castleshaw, Greater Manchester – Readhead, 1992 and 1993), would indicate that shaft furnaces were robust structures, sometimes constructed from stone with an inner clay lining. Possibly some of the tin-smelting furnaces may also have been equally robust in construction, perhaps even being constructed from granite blocks. Tin ingots have been found throughout Cornwall. Most are plano-convex in shape, although other shapes are recorded. The plano-convex ingots were either formed *in situ* or tapped into a pit adjacent to the furnace (Gerrard 2000, 20). This technology dominated the tin industry well into the medieval period (Gerrard 2000, 129).

5.4.2.1 Excavated examples

No reliably recorded excavations have been carried out on pre-blowing house tin smelting sites and probably the most reliable description of a '*'Jews' House'* type of furnace is given by Le Grice (1846). Earl (2002, 109) draws attention to this deficiency and comments, *'it is surprising that so little attention has been given to the earliest developments of mining and smelting technology of the UK'*.

5.4.2.1.1 Chûn Castle, Cornwall

Chûn Castle, a hillfort, possibly dating from the Iron Age, located near Madron, Penzance is about 84m in diameter. During excavations in 1925 several small smelting pits were discovered. Leeds (1926) reported on the discovery of the furnace and described it as a large furnace about 10ft (3.05m) long and 5ft (1.5m) wide constructed roughly from stone. The furnace had three fire holes each with a flue leading out to the south side. There was a fourth flue on the east side leading to the fire hole. Charcoal rich soil was found in the fire holes and the flue. Around the furnace there were various platforms and slag and charcoal were evident. Tin-dross and slag were found in an adjacent hut. The author agrees with Tylecote (1990, 42) that the interpretation presented by Leeds (1926) is probably incorrect. Tylecote suggests that it was a crucible furnace (for melting tin), however the description could equally be valid for three separate smelting furnaces, and could only be verified by a detailed examination of the smelting residues. Leeds (1926) also reports that a circular receptacle had been found at Chûn, the dimensions of which were similar to plano-convex tin cakes and this suggested that cakes may have been formed in the receptacles. Figure 5.4.1 shows the excavated furnaces.

5.4.2.1.2 Crift, Cornwall

The Crift site was first identified by spreads of tin slag in 1975 (Buckley and Earl 1990, 66 - 67). In 1989 a systematic examination was commenced. The site contained an estimated 100cwt of tin slag. Further down the field a large smithing hearth bottom had been found as well as a stone grooved hammer (Buckley and Earl 1990, 66 - 67). A trench down to a consistent depth of 2.5ft was dug across a circular feature identified by aerial photography and survey. Finds in the excavation were consistent with tin dressing and smelting, for example fragments of ‘crazing’ stone, furnace lining and tin slag. A horizon that contained fine charcoal and hammerscale was also identified. Beneath this horizon there was a shallow pit that had been partly excavated in the sub-soil and formed from small stones. The pit had been lined with a mixture of clay, sand and granite fragments up to 1.5 inches in thickness, its purpose is unclear, but it is presumed it was associated with some form of metal-working activity.

A 'furnace-hearth' feature was also excavated. It was a three-sided rock structure resting on broken granite. No furnace lining was found adhering to the rock but an examination of the areas between the rocks and the base produced three pieces of ceramic material and furnace lining fused with tin slag. Several tin slag dumps were found close to this feature (Buckley and Earl 1990, 72).

To try and identify the extent of metal-working activity a team from Bradford University, Department of Archaeological Sciences undertook a survey of the site in 1992 (McDonnell 1993, 48 - 50). This included a surface and vegetation, and geophysical (earth resistance, fluxgate gradiometer and measurements of soil magnetic susceptibility) survey. A buried telephone cable affected the fluxgate gradiometer data, however the other methods detected anomalies. Overall, this preliminary survey showed that the site was located on a small spur of land and was more extensive than first thought (McDonnell 1993, 48 - 50). The results of the excavation are shown in Figure 5.4.2.

Full excavations were conducted by Bradford University in 1993, 1994 and 1996 (McDonnell *et al*. 1995). The 1993 work identified a further house platform north of that identified by Buckley and Earl (1990). Excavation continued on the southern building and revealed a tip of disturbed and spread tin slag adjacent to the southwest corner of the building. The original building was similar in dimension to a Cornish long-house (12m long by 4m wide) with tin slag and broken stone tools used partly in the walls construction This building may also have contained two hearths. The two other building phases are believed to be later. A section was cut through the slag tip and this showed that the slag had been deposited over a period of time and was composed of smaller slag piles. Medieval pottery on the site suggests a date between the 10-14th Centuries AD. It is assumed that any tin processing site later than this would have been water-powered. The tin smelting activity has not been dated but it is probably contemporaneous. Tin slag was also found in the fabric of the long-house (McDonnell *et al*. 1995, 50 - 57). The excavation showed that there had been three phases of building.

5.4.2.2 Geophysically surveyed examples

There have been a number of geophysical surveys conducted on Cornish archaeological sites since the early 1990s. One principal concern was how the magnetic signature from granite would affect the data. All the surveys detailed in the sections below were conducted on granite. Although there were technical difficulties with some of the surveys overall the magnetism from granite does not appear to have any adversely affect. It appears to only subtly change the overall contrast of the survey and is dependant on the depth of cover to the granite.

5.4.2.2.1 Crift and Bodwen, Cornwall

Ground conditions at Crift: Rough pasture with bracken and clumps of brambles.

Ground conditions at Bodwen: Pasture.

Much of the site geophysically surveyed at Crift in 1992 was covered by dense bracken and brambles which had to be cleared by hand. The fluxgate gradiometer survey did not show significant responses from the area opened up by Buckley and Earl (1990). However, anomalies were identified on the earth resistance data around the excavation.

A geophysical survey in 1993 in the immediate area of the excavation was more successful. The fluxgate gradiometer readings were generally in the range -10nT to 7nT. A linear anomaly corresponded to an old field boundary that was removed in the 1950s. During 1996 a survey was carried out at the Crift excavation to examine any geophysical responses that might be attributed to the tin slag. Two fluxgate gradiometer surveys were undertaken in areas surrounding Crift. One at Windmill Park, immediately north of the Crift excavation, and the second at Bodwen, to the north-east, where a Bronze Age rapier mould had been found (Harris *et al*. 1977).

During deturfing around the main excavation, an area on the west side was noted to contain abundant tin slag. This was investigated by two trenches which effectively defined the limits of the slag. A 0.25m fluxgate gradiometer survey was carried out to determine (i) the presence of further archaeological features within the blocked out area and (ii) examine the likely geophysical responses from concentrations of *in situ* tin slag. Figure 5.4.3 shows the position of the geophysical grids relative to the excavation. The raw data required very little processing and varied from -34nT to 521 nT. The high positive values are clustered around an iron survey nail left in the ground from the 1993 excavation work. Areas of negative values were mainly associated with the two trenches. The ground between the two trenches that had been deturfed produced positive values above 5nT and frequently above 10nT. A linear feature traverses the four grids from bottom left to top right. It is probable that this is related to the earlier field boundary identified on the 1992/93 surveys. There are no significantly high responses from the tin slag to enable its distribution to be evaluated.

At Bodwen Farm, about 1 km north-west of Crift, the abundance of artifacts in the form of flints, pillow stones, a rapier mould, an adze and a Cornish Round all indicate that the area has been settled for at least 3000 years (Harris *et al*. 1977) (Figure 5.4.4). The find of a rapier mould suggested that metallurgical activity had been carried out close by.

An extensive 1.0m resolution fluxgate gradiometer survey covered most of the area south of the Cornish Round. Most values fell within the -5 to 5 nT range and those outside the range tended to be associated with distinct anomalies. However, the majority of the anomalies identified had little contrast with the surrounding data. The data had a tendency to be positive on the eastern side of the survey area, a trend which may be a function of the underlying solid geology, granite. The ditch of the Cornish Round produced a very distinct anomaly. The survey is shown in Figure 5.4.5. No smelting sites were identified on the survey, but overall the survey was a success in showing that it is possible to survey granitic areas with no adverse effect to the quality of the data.

5.4.3. Blowing houses

Blowing houses (blowing mills in Cornwall) technology has been extensively researched (Greeves 1981, 85 - 95; Gerrard 1985, 175 - 182; Blick 1991, 23 - 30; Newman 1993, 185 - 197; Greeves 1994, 76 - 79; Gerrard 1994, 173 - 198; Greeves and Newman 1994, 199 - 219; Gerrard 2000) in both Cornwall and Devon. Numerous examples exist on Dartmoor and to a lesser extent Bodmin Moor. They were used primarily to smelt alluvial tin ore. Crossley (1994, 195) comments that by the end of the Middle Ages, blowing houses were well established. Very few blowing houses survive in Cornwall. Rose and Herring (1990) report that a survey of Bodmin Moor identified sixteen of them, mainly sited along the southern edge of the moor.

5.4.3.1 Excavated example

Gerrard (2000,129 - 139) provides a detailed explanation of how a blowing house and its components functioned. The house was mainly built from crudely cut granite blocks. Waterpower was used to work the bellows and, in many examples, stamps to crush the ore. The latter process involved the raising of a weight on the end of vertical rod by a water-powered rotating cam. At a point in the cam's rotation, the rod was released allowing the weight to drop onto the ore, which was placed on a mortar stone beneath the weight. Often (*personal observation*) the first indication of a blowing house is the presence of discarded heavily pitted mortar stones. Within the blowing house there are few visible features, but occasionally, examples of the float stone, the receiving trough for molten tin, and the mould stone may be found, as illustrated by Figure 5.4.6. Examples of excavated blowing houses are plentiful.

5.4.3.1.1 Upper Merrivale, Dartmoor, Devon

The Upper Merrivale blowing house was excavated between 1991 and 1994 (Greaves 1994, 76). The main component, referred to as mill 'A', had internal dimensions of 11m by 4m. During clearance of the mill floor a furnace structure, mould stone, bellows platform (with post holes), a channel leading from a stamping area and a stone lined pit were uncovered. A waterwheel pit was located outside the mill. The mill wall had been rebuilt on several occasions. Several discarded mortar stones were found built into the walls of the mill and the wheel pit. The furnace had been built against a massive granite boulder that formed the back wall. The furnace sides were two large granite slabs. The front of the furnace (as excavated) was open, but there was evidence of furnace lining, in the form of fire-hardened clay. The bellows platform was constructed from re-deposited material some of which was furnace lining and slag. Various channels were identified outside the mill that were thought to be associated with an earlier stamp mill. Tin slag was found throughout the site, some finely crushed for probable re-smelting. Peat charcoal was identified as the fuel (Greaves 1994). Figure 5.4.7 shows the excavation together with a reconstruction of the blowing house.

5.4.3.1.2 Retallack, Constantine, Cornwall

Ground conditions: Heavily wooded area with brambles on the floor of a narrow valley.

Retallack, is probably one of the better recorded Cornish blowing-houses. Gerrard (1985, 175) notes that it was documented in 1885 with the discovery of crazing (grinding) and mortar stones. The site contains one blowing house that probably dates from the early 16th century. The site is important as it includes all the elements associated with tin ore processing. There were apparently four crazing mills, two stamp houses and a blowing house (Gerrard 1985, 176). The stone walled blowing house contains a mould stone and the walls survive to a height of 1.5m (Gerrard 1985, 180). A plan of the site is shown in Figure 5.4.8. When Retallack was visited on the 25th March 1999 most of the site was covered in dense vegetation, making any form of geophysical survey or topographical interpretation impossible.

5.4.3.2 Geophysically surveyed examples

Two blowing house sites were geophysically surveyed in March 1999. One was in Cornwall, at Coombe / Millpool to the east of Bodmin, the other was Lower Merrivale on Dartmoor, Devon.

5.4.3.2.1 Coombe / Millpool, Cornwall

Ground conditions: Rough pasture with ruined buildings.

Coombe is probably one of the better-preserved blowing house sites (Figure 5.4.9). It consists of a granite building approximately 3.2m by 4.5m. Some of the walls are up to 1.8m high. A linear depression on the east side of the site approximately 5.5m long indicates the location of the waterwheel pit. There are various dividing walls on this split-level site and interiors are filled with granite rubble. Traces of slag were found down-slope of the house in the stream but there was no obvious slag dump. There is one mortar stone with four depressions indicating the waterwheel drove stamps as well as bellows. The purpose of the survey was to try and identify with a fluxgate gradiometer survey the location of the furnace, if not obscured by rubble, and the waterwheel pit.

A 0.5m resolution fluxgate gradiometer survey was difficult to conduct due to many obstructions on the site. Most of the data were negative. Positive data were recorded adjacent to walls and it was unclear whether they were generated by metal under the rubble. The results of the survey are shown in Figure 5.4.10. It was not possible to produce a reliable interpretation of these data, due to the discontinuous nature of the data. External to the structures it may just be possible to identify the waterwheel as a very weakly contrasting feature.

5.4.3.2.2 Lower Merrivale

Ground conditions: Interior of blowing house with wall tumble.

The Lower Merrivale site is part of a complex of three blowing houses located in the Walkham Valley, on Dartmoor, Devon (Greaves and Newman, 1994). The house is built into a granite bank on the east bank of the River Walkam. The mill is constructed from irregularly shaped granite blocks. It measures roughly 10m by 4m and contains a float and mould stone. Several slabs of burnt granite identify the furnace position next to the float stone (Figure 5.4.11).

A 0.25m resolution fluxgate gradiometer survey was conducted within the blowing house. The granite tumble both internally and externally restricted the extent of the survey. Most data fell between –10nT and 10nT but the area around the furnace generated values up to 38nT. As all the structure and floor of the blowing house is constructed from the same granite, it is concluded that this relatively high response anomaly is produced by thermo-remanent magnetism from the furnace. Remains of a furnace-binding collar constructed from iron, for example would have generated a considerably higher response. The surrounding granite walls had negligible effect on the survey.