An integrated geophysical and analytical appraisal of early iron-working: three case studies

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Abstract

Geophysical surveys are a standard method of site assessment. However very few are used specifically to evaluate structures associated with metallurgical activity. Routine geophysical surveys frequently encounter iron-working activity but this data is usually ignored as it tends to be excessively 'noisy' and difficult to interpret. A combination of geophysical surveying techniques were applied to three iron-smelting sites in North Yorkshire to investigate the effectiveness of geophysics in identifying iron-working activity.

Introduction

The first geophysical surveys of early iron-working sites were conducted in the 1950s, and utilised proton magnetometers. These early surveys identified positive magnetic anomalies that corresponded with furnaces and/or concentrations of slag. The absence of sophisticated computer techniques for displaying the data was also detrimental to its interpretation. By the 1990s surveys carried out with sensitive fluxgate gradiometers (magnetometers) combined with rapid computation had overcome these problems. The fluxgate gradiometer together with resistivity and magnetic susceptibility methods have now become the standard methods for geophysically surveying archaeological sites (Gaffney and Gater 1993).

Despite these innovations, iron-working sites have still not received much attention. Iron and iron slag can produce large responses in gradiometer data which can often mask the weaker responses generated by other features. Further, resistivity methods are thought to have limited use on iron-working site surveys as they do not respond to the more characteristic properties (strong magnetic signals) associated with early metalworking sites (McDonnell 1995). Magnetic susceptibility, however, is thought by some researchers to be a most effective method that can yield reliable information. It is a technique that has been used to determine slag distribution, and if carried out in conjunction with a topographical survey, it may be used to assess the volume of slag present (P Crew pers comm).

However, under the right circumstances, all three geophysical surveying methods (magnetometry, magnetic susceptibility and resistivity) may be used to identify discrete features on iron-working sites. To test this hypothesis, various combinations of geophysical methods were employed on three iron-working sites. These sites, The Grange at Chop Gate, Timberholme at Laskill, and Forge Farm at Rievaulx, are all located on the western side of the North Yorkshire Moors National Park in the Bilsdale/Rievaulx area (Fig 1).

Previous geophysical surveys on iron-working sites

During the 1960s and through to the 1980s proton magnetometer surveys were conducted on a variety of iron-working sites in Denmark, Germany, Czechoslovakia and Poland, mainly in areas known to contain slag pit furnaces (Smekalova *et al* 1993). A survey in 1965 at Drengsted, Denmark, for example, identified a series of magnetic anomalies which were proved by excavation to be groups of slag pit furnaces. Individual slag pits were also noted but it was usually the larger anomalies, composed of slag pit clusters, that were excavated (*ibid*).

By the mid 1980s a variety of geophysical techniques was being employed on sites in the Vosges, eastern France. At the Minier du Samson, Sainte Croix aux Mines in 1985, for example, a proton magnetometer survey identified positive magnetic anomalies which subsequent excavation proved to have been produced by slag tips associated with forges. The forges however were not discernible on the survey. Resistivity techniques were also carried out on the same site to try and established the depths of these anomalies (Fluck 1990 and Grandemange 1994). By the late 1980s similar geophysical survey techniques were being used in the Black Forest area of Germany to evaluate smelting sites (Goldenberg 1990).

Proton magnetometer surveys on iron-working sites were also conducted in England during the 1960s and 1970s. In 1969/70 a possible bloomery was surveyed with a proton magnetometer at Middlestown, near Wakefield (Bartlett 1971). The same technique was employed two years later by Leeds University at Lancaster where a

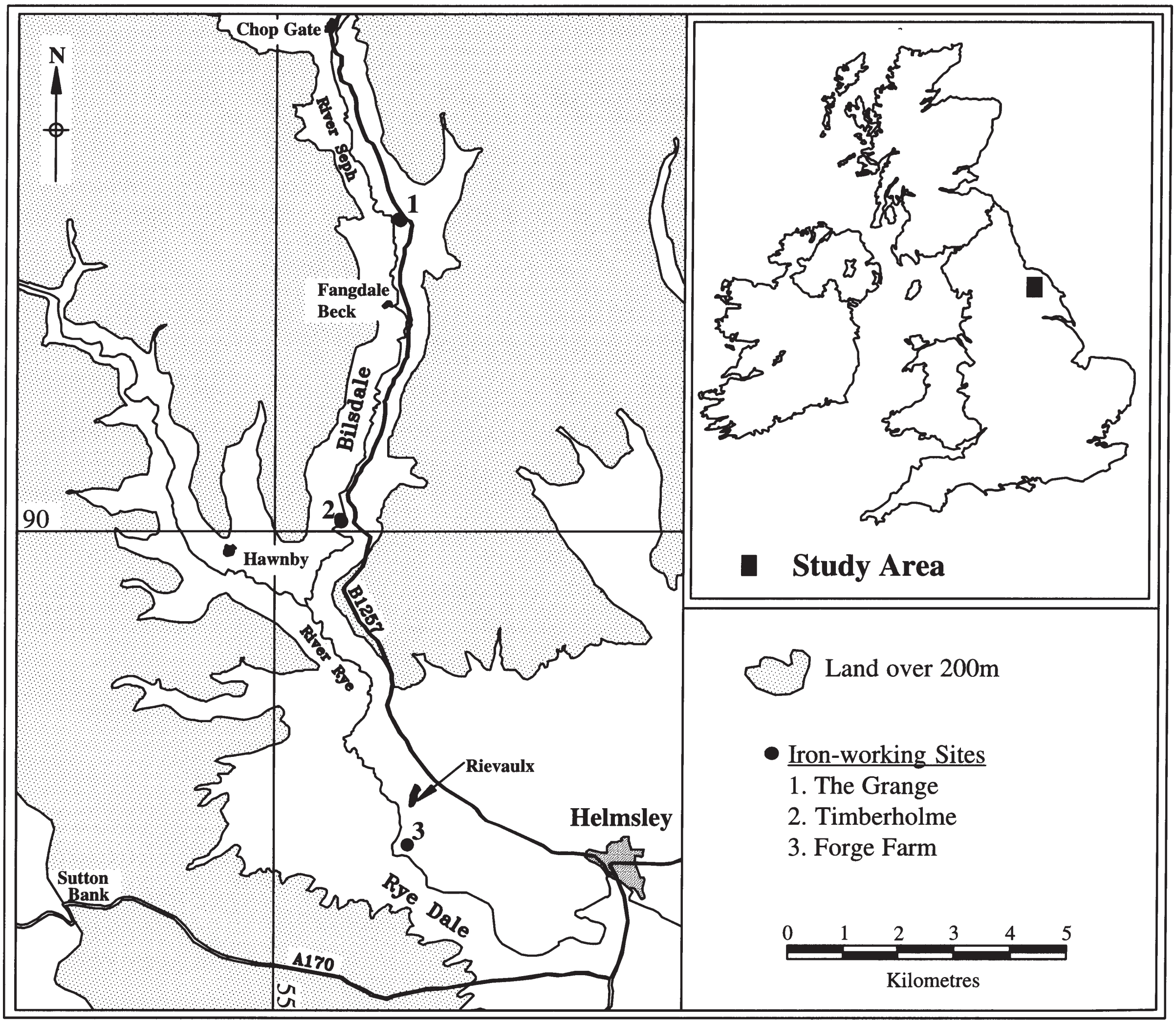

Figure 1: Location of sites mentioned in the text

possible Roman 'iron roasting hearth' was located (Jones and Shotter 1988). Neither account records detailed survey information, but investigation by R W Vernon has revealed that the former survey consisted of two traverses centred on a positive magnetic anomaly.

In the past ten years, the Ancient Monuments Laboratory of English Heritage has routinely carried out geophysical investigations on a variety of sites which have included evidence of iron-working. These have included Romano-British sites at Mantles Green, Amersham, Buckinghamshire (David 1982 and Yeoman and Stewart 1992) and Walton-le-Dale, Lancashire (Bartlett 1987). A survey report on a known smithy at Burton Dassett, Warwickshire detailed a new approach to magnetic susceptibility surveying. Testing of the smithy floor material provided a clear correlation between the varying magnetic susceptibility values and the distribution by weight of magnetic material (primarily in the form of hammerscale) within the samples (Mills and McDonnell 1992).

In Wales, P Crew has been systematically excavating iron-working sites in Snowdonia since the 1970s (Crew and Crew 1997). Crew has also employed geophysical techniques on various sites dating from late prehistoric to 14th century. One of the first sites to be surveyed was Bryn y Castell, near Ffestiniog. A proton magnetometer survey defined the spread of metallurgical debris (P Crew pers comm). However the magnetometer data from Snowdonian iron-working sites can be affected by responses produced by the underlying igneous and metamorphic rocks. Consequently magnetic susceptibility surveying, a technique that is not generally affected by the geological background conditions as it only responds to shallow anomalies, has tended to supersede magnetometer work on some sites. At Crawcwellt West, near Traws-fynydd, for example, a magnetic susceptibility survey was successfully correlated with the distribution of slag across the site (Crew 1990).

In the last six years several very detailed papers on the geophysical responses recorded on iron smelting sites have been published. Smekalova *et al* (1993) describe magnetometer surveying strategies employed during the examination of Iron Age slag pits at Snorup, Denmark. Subsequently excavation identified additional slag pits originally masked by stronger responses from adjacent pits. It was also possible to correlate the slag mass with the strength of the magnetic anomaly (*ibid*). In the Stumpf Forest, West Germany, Al-Mussay has examined the magnetic properties of different slag heaps. This research found there was a direct relationship between the intensity of positive magnetic responses and the thickness of slag deposits (Al-Mussawy 1990).

The interpretation of iron-working sites however has been limited by the lack of comparable research. Most magnetometer surveys only describe the geophysical responses which correlate with either the slag distribution or furnaces which can also mask other features associated with the iron-working activity. The geophysical interpretation of iron-working sites is further complicated by the wide range of geophysical responses that iron-working sites can produce. Gradiometer surveys of typical archaeological sites produce values in the range of ±10 x 10^{-9}T (Tesla). In contrast, iron-working material can typically produce values of ±2000 x 10^{-9} T. The data from gradiometer surveys of iron-working sites must therefore be examined in great detail to tease out the more subtle features. Few geophysical surveys have therefore been conducted to examine iron-working features other than the furnace and associated slag and further detail is usually provided by subsequent archaeological excavation.

The measurement of the geophysical properties of different types of slags could also aid survey interpretation. The Burton Dassett survey indicates what can be achieved by measuring the magnetic susceptibility of samples from a forge floor (Mills and McDonnell 1992). This principle can also be applied to slag samples. Such measurements could be correlated with iron content and thus be indicative of the process that produced the slag.

Objectives

The principal objectives of the research conducted on North Yorkshire iron-working sites was to assess the value of geophysical surveying, to determine what methodology should be employed and which technique would be appropriate for specific circumstances. The approach taken was two-fold: firstly, to survey sites to detail the iron-working activity and associated features; and secondly, to evaluate the types of iron-working activity carried out on the site by geophysically examining slags and comparing the results with the chemical composition of the slag. From this approach, it was hoped to establish bench marks for interpreting iron-working sites encountered during routine geophysical surveys. Five factors were considered at each site:

a) What was the extent of the iron-working activity?
b) What is the archaeology associated with the iron-working activity?
c) What detail could be identified on each site?
d) Did the iron working activity produce a characteristic site-specific response?
e) What technique or combination of techniques gave the best results?
It is only proposed to discuss factors a) to d). A future paper will discuss factor e).

North Yorkshire Moors: geography and geology

The investigated area lies on the western side of the North Yorkshire Moors National Park, west and north of Helmsley. The River Rye flows south-eastward to Helmsley through Ryedale, passing Rievaulx Abbey. Upstream of Rievaulx, the River Seph flows southward through Bilsdale to its confluence with the Rye near Hawnby. Both dales are deep, steep-sided valleys with wide flat alluvial floors. The lowest point in the study area occurs near Rievaulx Bridge, 75m AOD whilst the surrounding moorland rises to 400m AOD. The B1257 that runs northward from Helmsley, on the east side of Bilsdale, passes close to all three surveyed sites.

The solid geology of the Helmsley and Bilsdale area covers virtually the full sequence of Jurassic strata in Yorkshire. The principal rock types are limestone, sandstone and grit, often calcareous, and shale. In the lower part of the Jurassic these rocks may be interbedded with thin coal seams, jet and iron-rich horizons. The latter can form distinct massive ironstone bands which have been worked extensively along their northern outcrops in Cleveland. The principal worked ironstone bands are the Main, Dogger and Eller Beck Bed. All three horizons occur in Bilsdale, although the Main Band splits into four sub-bands (Fig 2) and has only been intermittently worked where it is thick enough (Hemmingway 1974).

Iron-working in the North Yorkshire Moors

The North Yorkshire Moors has a long tradition of iron-working stretching back to the Iron Age. At Levisham Moor, for example, 25 km east of Bilsdale, the excavation of an Iron Age settlement has provided ample evidence for the production of iron (Hayes 1978 and McDonnell 1986). Unfortunately no Iron Age sites have so far been found in the Bilsdale area. Similarly there is also no known evidence for iron-working having taken place in the area during the Roman period.

The earliest evidence for iron production in the Bilsdale area occurs in 1145. In that year, Walter Espec Lord of the Manor of Helmsley gave much of Bilsdale to the Cistercian Abbey at Rievaulx. At that time part of Bilsdale

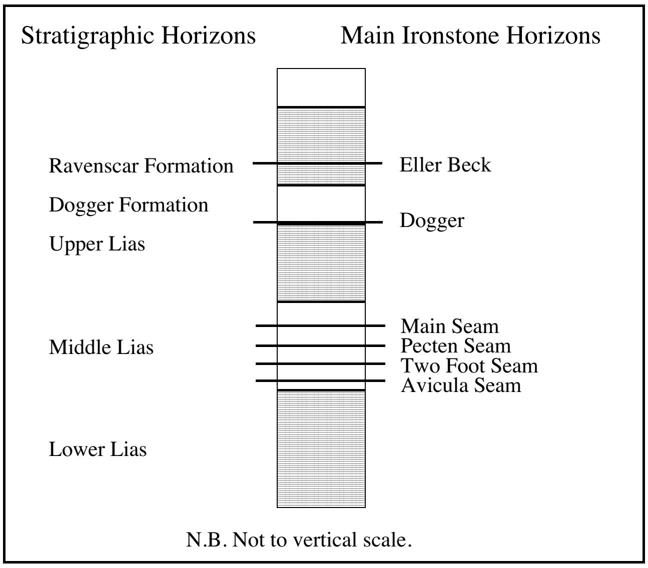

Figure 2: Principal Jurassic ironstone horizons in the North Yorkshire Moors (after Hemmingway 1974)

was referred to as Smiddesdal(e) (Smiths' Dale), a name of Nordic origin (McDonnell 1963). About 1170, a *ferrarius* (ironsmith) was operating north of Laskill for Stainton, now a lost village (McDonnell 1972). It was also during the 12th century, that the Cistercian order started to establish granges (Pratt 1969), outlying settlements, to administer or farm the more remote portions of the Abbey lands. Such communities could specialise in iron-working activities as part of their day to day operations (McDonnell 1963). The surveyed Grange site had been such an establishment.

At the dissolution of Rievaulx Abbey in December 1538, there is a reference to two 'bloomsmiths' in operation at Laskill, the bloom being transported to a hammer-smithy at Rievaulx. When the Duke of Rutland took over the Abbey lands in 1540 he also acquired the iron-smelting installations. Field work has identified Timberholme, the second site to be surveyed, as the only possible known location of the Laskill operation. Contemporary records suggest that the Rievaulx works were rebuilt in 1540 into a more advanced hammer-smithy. It may have been located in the precinct close to the Abbey (Coppack 1986).

In 1576 a blast furnace replaced the bloomeries and was built not at Laskill, but at Rievaulx (McDonnell 1972). The blast furnace was modified on several occasions and continued in operation until *c*1670 (Schubert 1957). The pigs of cast iron produced by the furnace were taken to and re-worked in a finery/chafery complex believed to be at Forge Farm, the third surveyed site. Figure 3 identifies the iron-working operations associated with the three surveyed sites.

The North Yorkshire geophysical survey

The three geophysically surveyed sites have now become part of a much larger project to investigate the iron-working industry of the North Yorkshire Moors. The area is considered to have a number of advantages which makes the application of geophysics worthwhile. The area has:

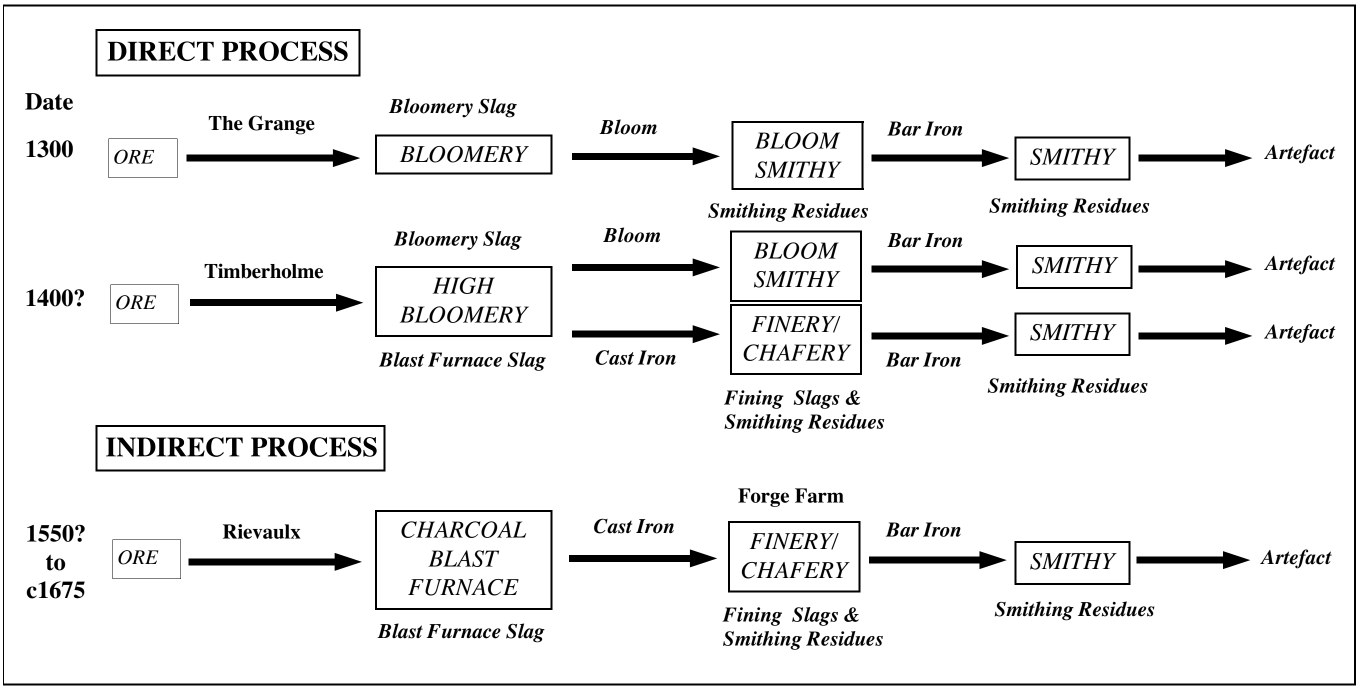

Figure 3: Chronological and technological relationships of the surveyed sites

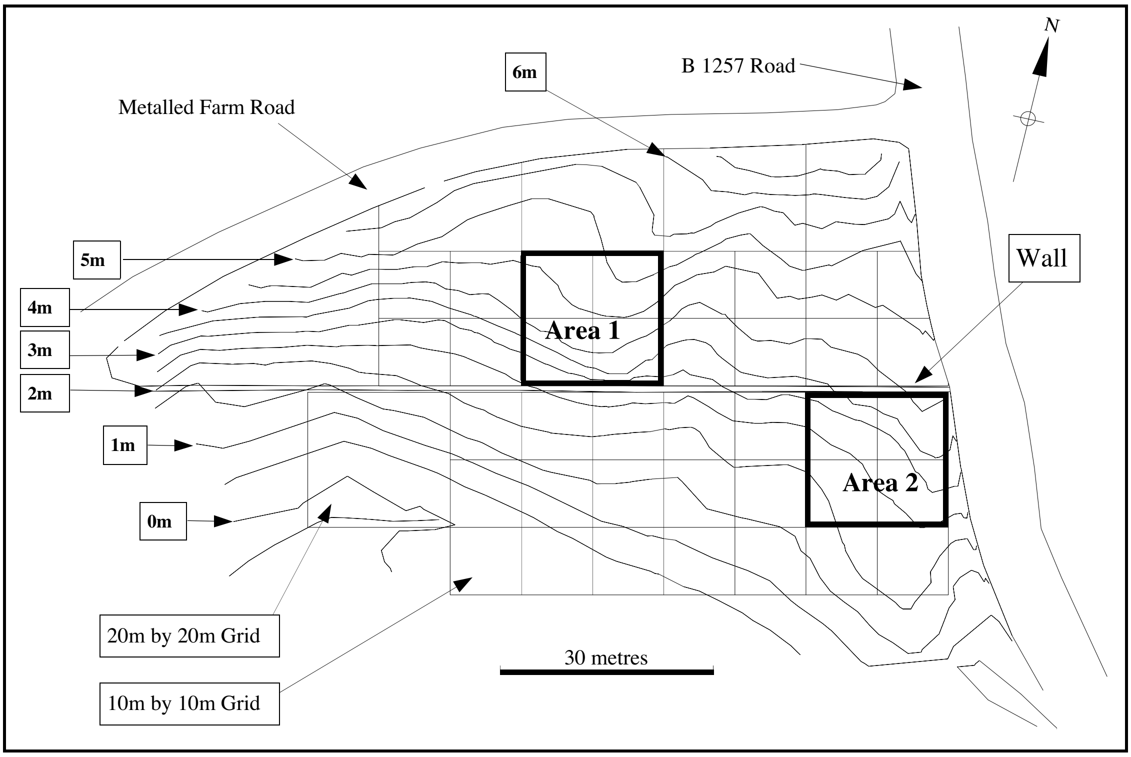

Figure 4: The Grange showing the fluxgate gradiometer survey grid superimposed on the surface contours. The magnetic susceptibility surveys were conducted in Areas 1 and 2

a) A proven chronology of iron smelting technology from the Iron Age to the 17th century.
b) Over much of the area there is no later, industrial revolution, activity to overlie the iron smelting sites.
c) Sedimentary iron ores that are all Jurassic in age (Hemmingway 1974). The ores are primarily chamositic siderites and have been formed in a similar manner.
d) Geology that is geophysically 'quiet' in the study areas.
The three sites chosen for the initial geophysical investigation were originally identified in the 1970s (McDonnell 1972) and exhibit a wide range of ages for on-site activity. They are thought not to have been substantially modified since iron-working activity ceased. The geophysical instruments used on the surveys were a Geoscan FM38 fluxgate gradiometer, a Geoscan RM15 earth resistance meter with a mobile probe spacing of 0.5m, and a Bartington MS2 magnetic susceptibility field coil. In addition soil and slag samples were taken from each site to measure their magnetic susceptibility in the laboratory. The slags were also analysed to determine their chemical composition.

A major portion of the surveys were conducted between June and September 1995 and were included in a Masters Dissertation produced later that year (Vernon 1995). Additional follow-up surveys were also conducted in 1996 and 1997.

Site 1: The Grange

The Grange, Bilsdale was originally identified by the field name Cinder Hills, the usage of which usually denotes a smelting site. The surveyed area is thought to be the site of a grange identified in monastic records (McDonnell 1985, 24) and lies close to the hamlet of Chop Gate. The site is bordered by roads on its north and east flanks and Ledge Beck flows along the south side. The surveyed area consists of pasture land that rises 6.5m in a north-eastern direction from Ledge Beck. It is divided by a straight east-west aligned wall. Several discrete hummocks, some composed of slag, break the natural lie of the land. At the foot of the slope an old stream meander or a man-made water channel is discernible. The underlying solid geology of the surveyed area consists of Lower Lias clay overlain to the south by alluvium.

Initially a 21 grid square fluxgate gradiometer survey composed of 10m by 10m metre grids and a 0.5m sampling interval, producing 400 readings per grid, was carried out between the east-west dividing wall and Ledge Beck. This area was chosen as it was thought that Ledge Beck may have been used to supply water to the site. After data processing, it was apparent that the area contained structures that extended north of the wall. A further 16 grid squares were surveyed in this area. This was followed by a final survey comprising of 5 peripheral 20m by 20m grids to infill minor gaps in the survey. The grid layout is shown on Figure 4 together with local ground contours generated from an EDM survey.

During the survey, problems were experienced in finding an on-site geophysically-'quiet' location where the fluxgate gradiometer could be calibrated. However despite this, the quality of the raw data was excellent. The data was processed using Geoscan Geoplot v 2.01. The data was not filtered as this would have reduced the responses produced by the iron-working activity. A plot of the raw gradiometer data is shown in Figure 5.

The survey identified the location of a variety of linear features and provided strong evidence for industrial activity. The significant area of high responses on the north side of the wall corresponds to a large grassed over hummock. South of the wall there are a number of unconnected high positive response areas, some of which form subtle surface features. Two areas were singled out for magnetic susceptibility investigation with 20m by 20m grids (see Fig 4). Area 1 is a possible slag tip that formed a topographical feature. On the gradiometer survey, this tip was characterised by a large grouping of positive responses with a large negative response on the south side. Area 2 is a low curved mound, which may have been disturbed. On the gradiometer survey it is a weak feature with a distinct grouping of negative responses along the southern flank. However, both magnetic susceptibility surveys were disappointing and provided little additional information.

The interpretation of the gradiometer data is shown in Figure 6. The site is characterised by a series of long linear anomalies trending north-west/south-east with shorter linear anomalies aligned at right angles. Two main groups of anomalies interpreted as areas of slag occur in the survey area, one located centrally (A) and the other to the east (B). The latter area is bow-shaped with linear anomalies interpreted as forming a small rectangular structure (H) on its northern limb.

Several areas of high positive values (G, J, K and L) seem to be associated with the linear features noted above. The largest (G) is roughly rectangular, and has a distinct negative halo around it. These anomalies may represent iron-working areas or other industrial activity requiring the use of a kiln or furnace, which on a grange site cannot be ruled out. To the north, a curved anomaly (C) appears to delineate a boundary to the structures. Another linear anomaly (D) trends into the area from the north-east. The high gradiometer responses associated with it, suggest that it could be a slag-filled ditch. On the south-east side of the survey, two linear anomalies (E and F) run south-eastward and downhill towards Ledge Beck, and may represent channels for taking water from the site.

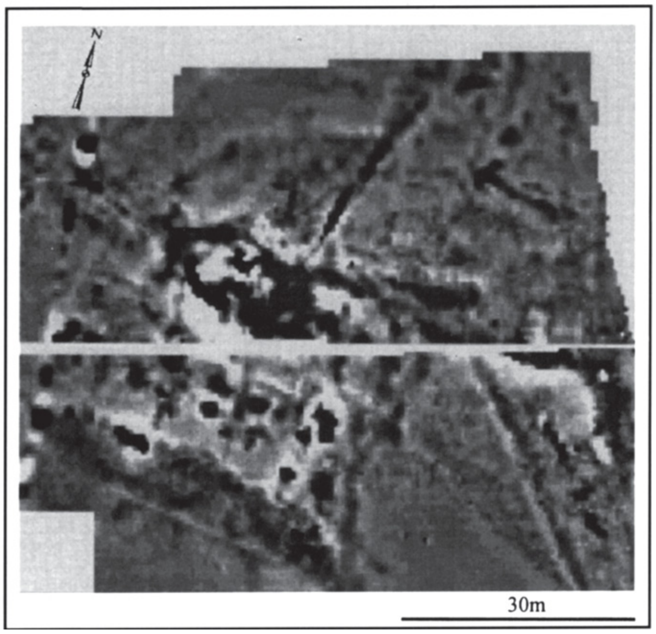

Figure 5: Raw fluxgate gradiometer data for The Grange. Clipped range -70nT (white) to 70nT (black)

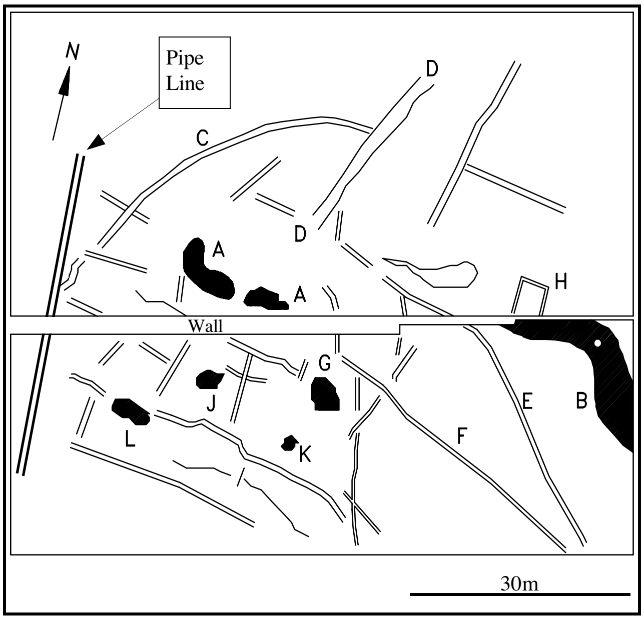

Figure 6: Interpretation of the fluxgate gradiometer data for The Grange

Clearly the geophysical survey of the Grange site has fulfilled several of the objectives. The extent of the iron working activity has been delineated and associated features have been identified. The relationships of these features also demonstrate that iron-working was an integrated function with other on-site activity.

Site 2: Timberholme

The Timberholme site lies close to the location of Laskill Grange on the River Seph. When previously visited by McDonnell in 1972, a silted-up leat was noted running

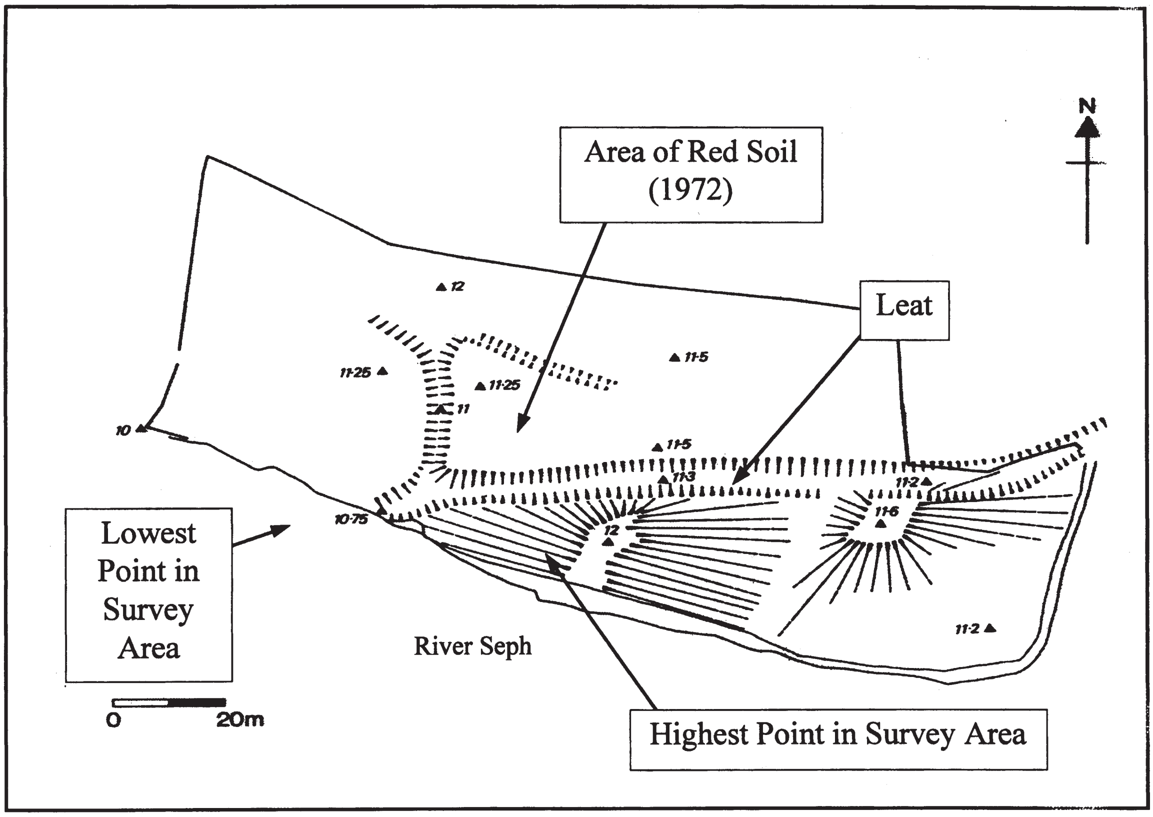

Figure 7: Topographical survey of Timberholme

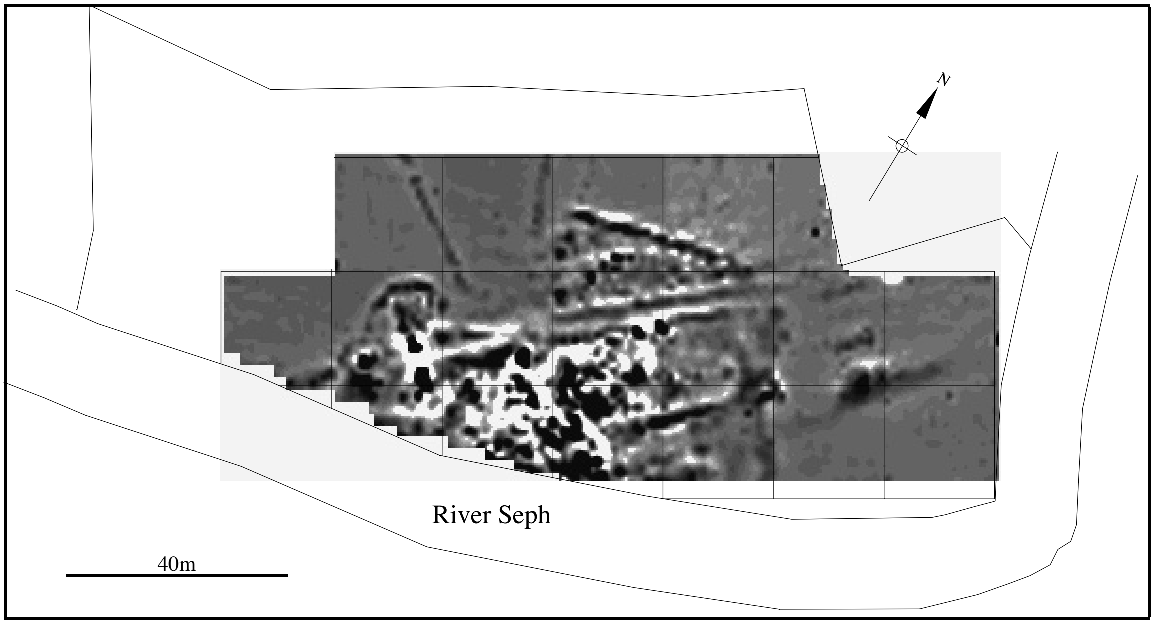

Figure 8: The 20m by 20m survey grids and raw fluxgate gradiometer data for Timberholme. Clipped range -44nT (white) to 50nT (black)

roughly east-west across the site close to a low-lying slag tip. An area of 'burnt soil' was observed to the north of the leat (McDonnell 1972). In 1995, the site was under tall grass but after it was cut, the leat and slag mound could be clearly seen. There are no areas of exposed slag, except in the bank of the river. The soil, revealed in animal burrows, overlies the slag heap and often exceeds 300mm in thickness. There is an elevation change of about 1.5m across the site from the lowest and highest points, in the leat and on the slag tip, respectively. The surveyed area is covered by alluvium. A plan of the site is shown in Figure 7.

A 20m by 20m grid fluxgate gradiometer reconnaissance survey (readings taken every 1m) was conducted across the whole of the site. The raw data from the survey clearly show the route of the leat and the extent of the slag tip and is shown on Figure 8. Two areas contained features requiring a more detailed investigation using 10m by 10m grids. The first detailed survey was conducted over a large positive response at the western end of the slag tip associated with a square anomaly. This lies adjacent to the previously recorded area of burnt soil and immediately on the north side of the leat. The results from the detailed survey are shown on Figure 9. The second survey was conducted over the eastern end of the slag heap across a linear anomaly which runs parallel to the leat. The latter survey did not reveal any further interpretable data. Both the 10m by 10m grid areas were surveyed with the earth resistance meter.

A 20m by 20m grid magnetic susceptibility survey was also carried out over much of the site together with a 10m by 10m grid survey over the square feature referred to above. The results from this survey are shown in Figure 11.

The interpretation of the gradiometer data is shown on Figure 12. The leat (A) traverses the site and at its western end (B) turns sharply south and runs into the River Seph. A large area of slag (C) lies between the river and the leat. A square structure covering an area of about 10m by 10m (G) with an outer wall (D) is located on the north side of the leat. This structure is interpreted as a furnace site. The detailed earth resistance survey across it confirms the gradiometer results (Figure 10). The structure surrounding the furnace appears to continue southward to the river and may have been used to divert the leat water back into the river. Two areas of high gradiometer readings (E) positioned immediately south of the furnace could represent the remains of the demolished furnace, bridging or infilling the leat. North of the leat, two linear anomalies (J and K) stop short of it. The leat also cuts through a trapezoid-shaped anomaly (F) which could either be the remnants of an earlier enclosure, or possibly the retaining walls of a pond or simple reservoir. Areas of high responses within this feature suggest that it may have been partially backed-filled with slag at a later date. This reservoir could be linked to an industrial phase that preceded the water being supplied solely by a leat. The occurrence of slag north of the leat suggests that feature F was not in use during the final phases of iron-working activity on the site. There are also indications of a water by-pass or overflow channel (H) running south from the leat east of the slag heap. This is observed on the surface as a slight depression. A further discrete area of slag (M) lies to the east of the by-pass channel.

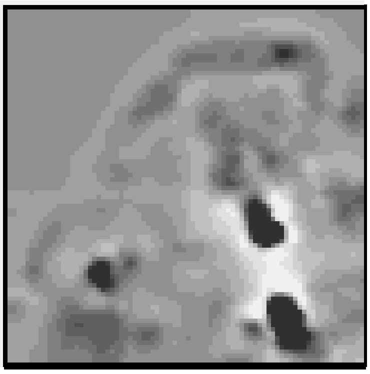

Figure 9: Raw fluxgate gradiometer data over a 20m by 20m area at Timberholme showing a square structure. Clipped range -150nT (white) to 150nT (black)

Figure 10: Raw earth resistance data over a 20m by 20m area at Timberholme showing a square structure. Clipped range 67 ohms (white) to 135 ohms (black)

The magnetic susceptibility data clearly show the slag distribution and the leat. Relatively low responses are associated with the square structure interpreted as a furnace, but there are small areas of higher positive data suggesting some response to features identified by the gradiometer. It is probable that after abandonment this site was subjected to flooding. The thickness of soil and alluvium across the site will have affected the magnetic susceptibility responses from the underlying slag. The magnetic susceptibility method, using a small diameter field coil (205mm external diameter) will only record responses from the upper soil layers compared to the potential for examining deeper structures offered by both gradiometry and resistivity techniques (Batt *et al* 1995).

This survey has been very successful. It has identified the extent of iron-working activity and the associated archaeology. The presence of a linear ditch across the site was known at the onset of the survey. The geophysical work confirmed that an ancillary leat ran from the main leat to the area adjacent to the anomaly interpreted as a furnace. (The ancillary leat is currently being interpreted as a leat to drive the bellows waterwheel). The possible revision of the system supplying water to the site, from a simple reservoir to a direct leat, could suggests that there

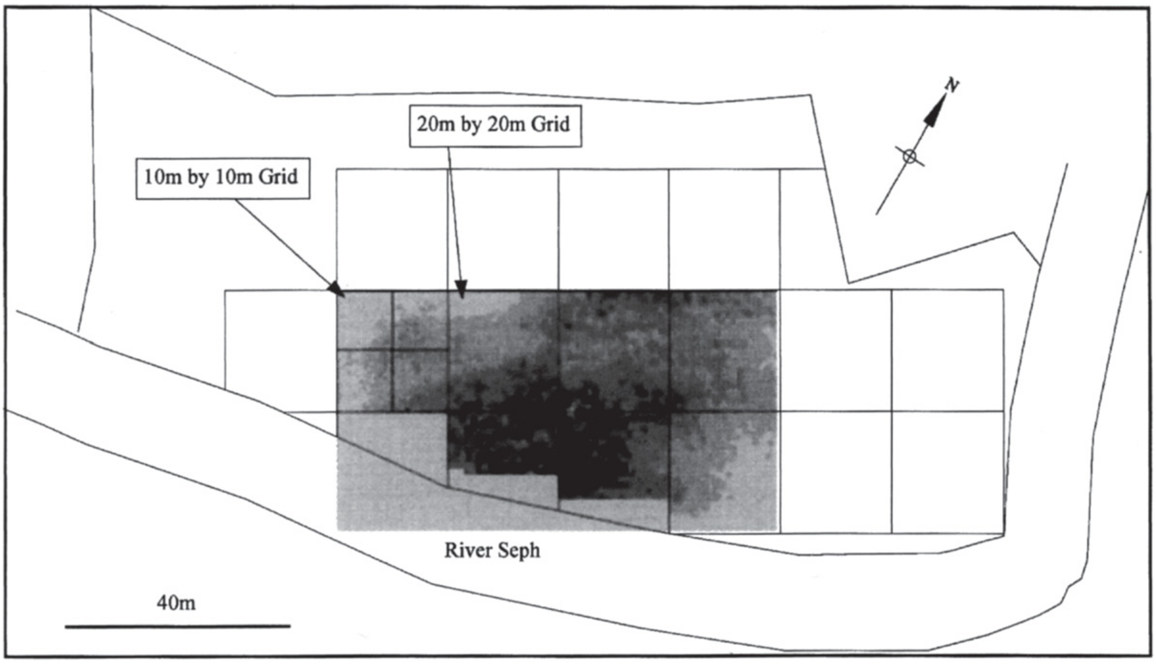

Figure 11: Magnetic susceptibility data and grids at Timberholme. Clipped range 0 (white) to 900 x 10^{-5} (SI) (black)

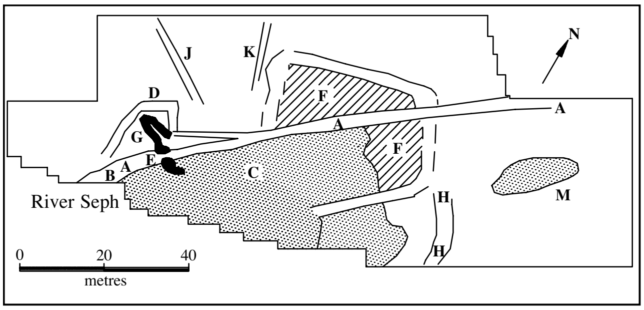

Figure 12: Interpretation of the fluxgate gradiometer data from Timberholme

was more than one phase to the site development. This is corroborated by evidence from the magnetic susceptibility values obtained from slag samples which is discussed in a later section.

Site 3: Forge Farm

The Forge Farm site, near Rievaulx, Ryedale, is dominated by a prominent mound of slag. The surveyed site lies in rough pasture adjacent to a minor road east of Rievaulx Bridge between Forge Farm Cottage and a disused water channel, frequently referred to as a 'canal', that runs south from Rievaulx Abbey (McDonnell 1972). The survey was conducted to establish if there were any buildings associated with the tip. The slag tip rises about 1.6m above the surrounding ground, but falls steeply eastward to the level of the silted up canal. Figure 13 is a plan of the EDM topographical survey. The site lies entirely on alluvium.

As the site appeared to have a well-defined slag tip and a

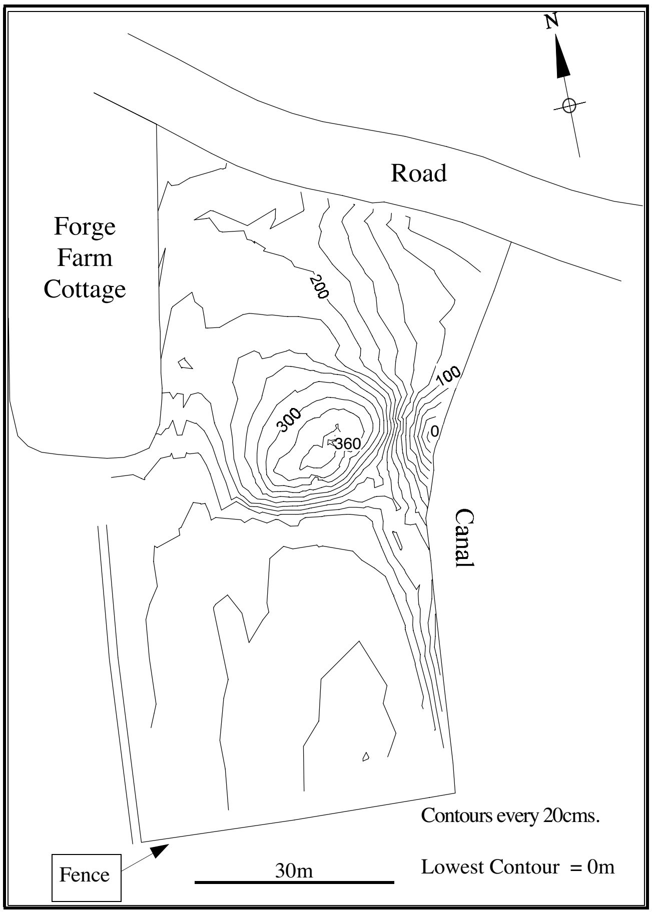

Figure 13: Topographical survey of the site at Forge Farm

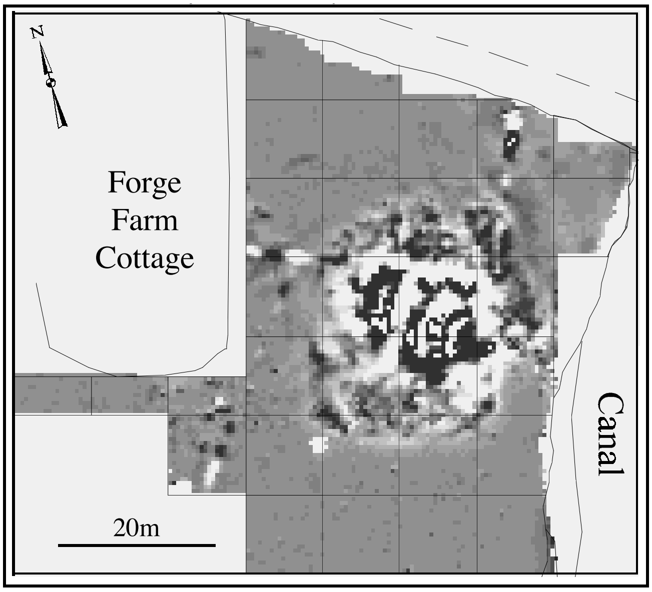

Figure 14: Raw fluxgate gradiometer data from Forge Farm. Clipped range -260nT (white) to 234nT (black)

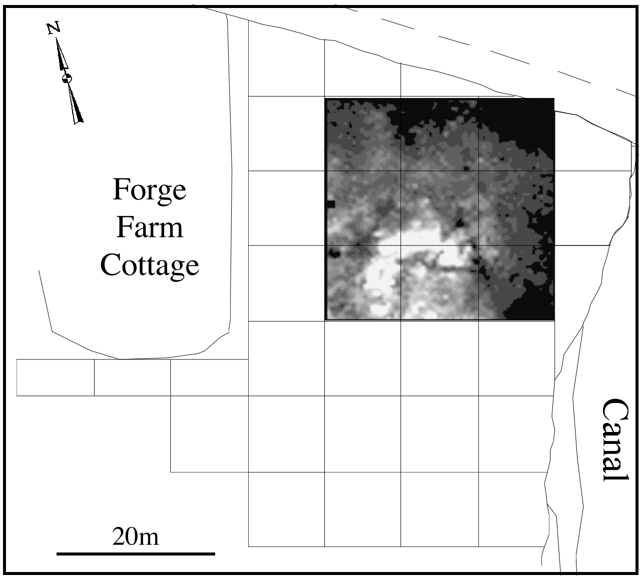

Figure 15: Raw earth resistance data from Forge Farm. Clipped range 300 ohms (white) to 520 ohms (black)

lack of other obvious structures, a 10m by 10m grid gradiometer survey was initially carried out over the slag heap and adjacent ground. This was later extended northward over a flat area that may have contained a finery/chafery, as hammerscale was noted in the soil. A westward extension of the survey investigated a possible leat extending in a southerly direction from Forge Farm Cottage. The search for the leat was inconclusive as the construction of a septic tank had disturbed the ground. However the new data revealed a possible structure on the flat area on the north side of the tip. It was noted that this corresponded to a prominent light brown summer parch marking. The raw gradiometer data is shown on Figure 14.

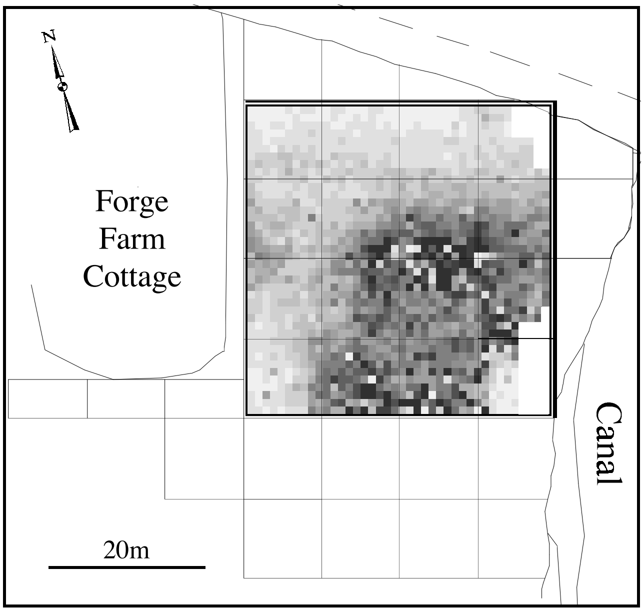

Figure 16: Raw magnetic susceptibility data from Forge Farm. Clipped range 50 x 10^{-5} (SI) (white) to 800 x 10^{-5} (SI) (black)

An earth resistance survey comprising nine 10m by 10m grids was also carried out over the scorch mark and southward onto the tip. These results are shown in Figure 15. However in the dry summer of 1995, the ground conditions produced problems with circuit coupling when surveying the tip. Also values of up to 500 ohms were not uncommon. However these high values are exceptional and later testing after a period of rain produced values of less than 100 ohms.

A magnetic susceptibility survey composed of four 20m by 20m grids did identify the tip, but not as precisely as the gradiometer survey. As would be expected, areas of exposed slag produced the highest magnetic susceptibility readings. Lowest responses are in areas where the tip is covered by soil. The magnetic susceptibility data is shown in Figure 16.

The interpretation of the fluxgate gradiometer data is shown in Figure 17. The extent of the slag tip (A) is clearly delineated. On the north side of the slag tip the survey revealed a rectangular feature together with a circular feature (B). This may be produced partly by slag removal. A linear anomaly running along the north-east side of the heap could be a filled-in channel (C). Surface observations suggest that the channel ran through a breach into the Rievaulx Canal at (D). Immediately to the south of this channel feature, there is a mound of non-slag material (responses are considerably lower than those produced by the slag). It is suggested that as it is located adjacent to the canal it may represent material removed from the canal embankment to form the breach referred to above. A linear feature (E) runs east from Forge Farm Cottage towards

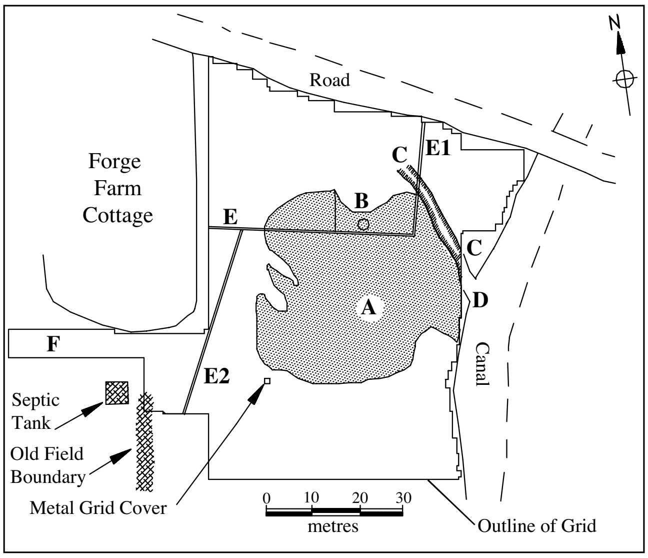

Figure 17: Interpretation of the geophysical data from Forge Farm

the slag tip. The pattern of positive and negative data suggests that this is a metal pipe. The resistivity data does confirm the route of this feature across the tip. The pipe turns north at the eastern end of the tip (E1). A branch pipe runs south on the western side of the tip (E2). The western side of the gradiometer grid (F) extended over the area where a leat, noted to the south, runs south from Forge Farm Cottage. However the ground had been disturbed in this area by the construction of a septic tank and the leat was not identified on the survey.

The Forge Farm survey revealed very little additional information to that obtainable by surface observation. The survey confirms the 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 face of the tip. Features revealed by the survey may be contemporary with the development of the slag tip. Anomaly B is enigmatic. It could be a structure, but the generated responses could equally have been produced by an area where the slag had been excavated.

Analyses of Slag Samples

Hand specimens of slag from each site were collected for analysis and determination of their magnetic susceptibility. To analyse them, a thick section was first cut from each sample using a diamond wafering blade. The samples were then mounted in conducting Bakelite, ground and polished in the usual manner. The thick sections were then examined under reflected light to determine the mineral texture. They were then carbon coated and analysed using a scanning electron microscope with an attached energy dispersive X-ray analysis system. All elements heavier than sodium (Na) were detected and the results were then converted to oxides (Fe results are calculated as FeO).

Table 1 shows the results from the slag analyses together with the magnetic susceptibility values. It also includes for reference an average analysis of 30 slag samples that have been produced by the direct process as well as a comparable sample from the Rievaulx blast furnace. The analysed samples taken from each site are listed below together with a description of their morphology and comments on their composition.

Site 1: The Grange
Type: Bloomery (one sample analysed). Sample Code: NYM2
Slag morphology: Typical ropey tap slag.
Mineralogy: Silicate laths in a glassy matrix with some free iron oxide.
Composition: This slag is rich in magnesia, alumina, silica and lime and low in iron oxide compared with the reference analyses. Table 2 (after Percy 1864) shows that the local iron ores also contain significant percentages of magnesia, alumina and lime.

Site 2: Timberholme
Type: High Bloomery (?) (three samples analysed).
Sample code: NYM4. Slag morphology: Frothy slag.
Mineralogy: Lath silicate and hercynite in a glassy matrix.

Sample code: NYM5. Slag Morphology: Tap slag.
Mineralogy: Globular iron oxide dendrites (Fe_2O_3/Fe_3O_4) (90%) in a glassy matrix (5%) with some metallic prills present (5%).

Sample code: NYM7. Slag Morphology: Tap slag.
Mineralogy: Glassy with a few metallic prills.

Compositions: Sample NYM4 is similar to the reference slag composition, but is significantly enhanced in magnesia. NYM5 is rich in iron oxide, indeed the corrected analysis would indicate that the iron oxide is present as magnetite and/or hematite. Given the slag morphology this is an extremely interesting composition. The hand specimen has a typical flowed tap slag, but its composition is radically different from other tap slags and hence raises questions concerning the validity of relying solely on morphological classification of slag. Sample NYM7 again displayed a classic tap slag morphology, yet its composition is very close to that of the Rievaulx charcoal blast furnace slag (NYM1). More importantly the analyses show a contrast between NYM4 and NYM7 and this would support the hypothesis that Timberholme was a high bloomery. It could operate either as a bloomery producing malleable iron and bloomery slag (NYM4), or as a blast furnace producing cast iron and a form of blast furnace slag (NYM7).

Table 1: Comparison of the chemical analyses of slags with their magnetic susceptibility values

Site		The Grange	Timberholme	Timberholme	Timberholme	Rievaulx	Forge Farm
Type		bloomery	bloomery	?	high bloomery?	blast furnace	finery/chafery
Slag Type	smelting slags	tap	dross?	tap	tap	blast furnace	?
Code		NYM2	NYM4	NYM5	NYM7	NYM1	NYM6
Na_2O	0.2	0.8	0.6	0.7	0.0	0.4	2.7
MgO	1.0	7.0	2.3	0.8	3.6	2.5	0.3
Al_2O_3	5.5	9.7	9.0	1.1	15.2	15.2	0.3
SiO_2	28.4	26.2	33.3	6.2	37.0	55.5	9.2
P_2O_5	1.0	2.4	2.1	0.7	1.3	0.0	9.5
K_2O	1.5	1.4	1.6	0.1	2.2	2.5	0.6
CaO	5.1	7.8	13.6	2.6	28.5	17.5	2.3
TiO_2	0.4	0.4	0.7	0.1	1.1	0.9	0.0
MnO	3.4	1.3	1.2	0.3	1.4	1.0	0.5
FeO	53.1	44.7	34.7	74.8	5.3	4.4	76.3
CoO	0.2	0.2	0.1	0.2	0.2	0.6	0.2
CuO	0.0	0.2	0.2	0.2	0.1	0.2	0.2
Total	99.8	102.2	99.3	87.6	95.8	100.6	102.0
Magnetic Susceptibility (m^3kg^{-1})x10^{-6}		1.9	3.2	7.7	4.0	1.0	4.8

Rievaulx
Type: Blast Furnace [AD1576-1647(?)] (one sample analysed).
Sample code: NYM1. Slag Morphology: Charcoal blast furnace slag.
Mineralogy: Glassy with a few metallic prills.
Composition: Analyses show a typical charcoal blast furnace composition. The iron oxide content is extremely low (*c* 5%).

Site 3: Forge Farm
Type: Finery/Chafery [AD1576-1647(?) or earlier] (one sample analysed).
Sample code: NYM6. Slag Morphology: Varied, from flowed tap to massive blocky slags.
Mineralogy: iron oxide dendrites with some silicate in a glassy matrix.
Composition*:* the slag displays the expected high iron oxide level. The phosphorus content is extremely high.

Magnetic susceptibility of the slag samples

Samples NYM5 (Timberholme) and NYM6 (Forge Farm) have high magnetic susceptibility values due to the presence of high percentages of iron oxide. These higher values are due to the presence of both metallic prills and iron oxides in the slag. Samples NYM7 and NYM1 both have a low iron content and consequently low magnetic susceptibility values. NYM1 is a characteristic blast furnace slag, whilst NYM7 is from the Timberholme site and supports the presence of a high bloomery operation on the latter site.

Discussion

Unlike other deposits of metallic ores (lead, copper or zinc), iron minerals are common throughout most of Britain. However, whilst most areas yield evidence for iron smelting, the actual technology varies according to the

Table 2: Chemical analyses of two of the main Jurassic ironstone horizons (after Percy 1864)

Ironstone horizon	Avicula	Dogger	Dogger	Dogger
Na_2O	0.00	0.00	0.00	0.00
MgO	6.48	6.63	4.93	8.59
Al_2O_3	11.07	10.36	12.40	7.85
SiO_2	13.51	26.22	28.77	14.15
P_2O_5	0.69	0.27	0.37	0.10
K_2O	0.00	0.00	0.00	0.00
CaO	17.07	9.32	14.69	6.56
TiO_2	0.00	0.00	0.00	0.00
MnO	0.72	0.65	0.62	1.08
Fe_3O_4	50.46	46.54	38.21	61.68
Total	100.00	99.99	99.99	100.01

period and possible location.

The North Yorkshire Moors National Park contains many examples of iron-working sites that have not been disturbed by later iron-working technology. The different technologies (bloomery, high bloomery, blast furnace and finery/chafery) are spatially separated which enables a distinct chronological sequence of technological changes to be recognised and examined in a local context.

Many of the linear anomalies identified by the Grange survey, for example, are consistent with features that might represent walling and ditches. The rectangular pattern of linear anomalies is interpreted as building outlines. The limits of these features also correspond to changes in the surface topography. The presence of iron smelting activity is confirmed by the slag heaps and the slag-filled ditch. Medieval iron-working sites excavated elsewhere in the England are shown to contain a variety of features associated with the process. Money (1974) describes excavations on a medieval iron-working complex at Minepit Wood, Sussex and has identified areas for roasting/burning ore, hearths and charcoal storage. Ample evidence was found for the use of timber-framed structures and linear wattle/hurdle fencing (*ibid*). It is not unreasonable to presume that many of the geophysical responses at the Grange are associated with similar industrial activity. Further, this site would have also included farming enclosures together with storage and dwelling areas. It has been suggested that other granges attached to Rievaulx may also have supported smelting activity (McDonnell 1963). However, without further evidence, the usage (apart from iron-smelting) and origins of the Grange site are inconclusive. The smelting activity would date from about the 12th-13th centuries and had probably ceased by the time the Timberholme complex was operating (*c*1500). Smelting activity would probably have been associated with the initial construction of the Grange or represented a continuing industrial activity as part of the farming year.

On the Timberholme site, the surveys have revealed structures that are consistent with a water-powered operation. The identified square feature lies immediately on the north side of the leat and was large enough to have housed a furnace. The area of burnt ground noted in 1972 lies immediately to the east of this feature. Analysis of the Timberholme slag has shown that some slags have low iron content and are comparable with blast furnace slag, whilst other analysed slags have a similar composition to bloomery slag. These contrasting analyses could all point to a high bloomery being in operation on this site.

The layout of the Timberholme site can be contrasted with an iron-working complex recently excavated at Bordesley Abbey, near Redditch (Astill 1993), a site also operated by the Cistercian order. At Bordesley, a water powered workshop together with a mill pond and leat system underwent various modifications between the 12th and 15th centuries. The archaeological excavation proved that water was channelled to an undershot paddle wheel along wood-lined launders. Finds included a stone bearing, trip wheels and cogs indicating that the waterwheel was operating hammers (*ibid*). Unfortunately the Bordesley excavations yielded very little slag residues and it is argued that the Bordesley site was only a smithy. Illustrations, based on the archaeological evidence, show a roofed open-sided timber-frame structure surrounding the hearth area (*ibid*). The Timberholme structures may have been similar as they are thought to be contemporary with Bordesley. The significance of Timberholme, when placed in the context of how iron-smelting technology in Britain has evolved cannot be understated. No other high bloomery sites have been recognised in the British Isles though examples are known to have existed in Germany and Sweden (Tholander and Blomgren 1986).

On the Forge Farm site it has not been possible to identify a hearth or smithy in the surveyed area. There is no conclusive evidence to state that the rectangular anomaly (Fig 17, B) on the north side of the slag tip was associated with any iron-working activity. The canal running south from Rievaulx Abbey widens out immediately to the north of the survey area and was used as a reservoir after the monastery fell into disuse. A leat has been identified running from this reservoir to Forge Farm (Vernon *et al* in press). For the period that it was operating, a finery/chafery would have utilised waterpower. Tylecote (1986) shows several illustrations of finery/chafery sites. If one had existed in the surveyed area, it would have been identified. Physical evidence indicates that the finery/chafery may have been located on the site of Forge Farm Cottage as a distinct linear hollow runs southward from the cottage, suggesting a leat. The morphology of the slag tip would also suggest that the slag was brought onto the tip from the direction of the cottage. In this instance the geophysical survey has confirmed the extent of the tip.

Conclusions

The three North Yorkshire surveys have shown that geophysics can yield valuable information on the archaeology of iron working sites, and is worth pursuing. It should be emphasised that geophysical surveys alone do not provide all the answers but are an essential part of an integrated approach for investigating iron-smelting sites. Other techniques are surface observation and mapping, fieldwalking, target excavation and ore and slag analysis. The examination of appropriate documents, for example estate surveys etc, are also very relevant. One of the main benefits from geophysical surveying is that it can locate specific features (*eg* furnaces) under the right conditions with high precision, which facilitates target excavation.

Previous surveys of iron smelting sites have been used to identify geophysical anomalies which may represent the location of furnaces or scattered slag. The North Yorkshire surveys have gone beyond this application. They have provided clear interpretable information on all three sites and have therefore made a significant contribution to the interpretation of iron-smelting technology at these relatively uncomplicated locations. When the geophysical responses are further examined in conjunction with slag typology and composition together with the historical setting for each site, an even clearer picture of site use can be constructed. Whilst the three sites do not represent the full range of iron-working technology, it has been shown that geophysical surveys should be an essential part of the archaeological examination of iron working sites.

The data obtained by gradiometer surveys provides more structural/archaeological detail than magnetic susceptibility; however both surveys should be examined in conjunction with each other. Resistivity surveying should also be used as under the right circumstances it can clarify individual points of detail.

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