CHAPTER 10: FORMATION PROCESSES: THE FIRST IMPRESSIONS

10.1 Introduction

Previous chapters have evaluated the magnetic data analysed from Romano-British, medieval and post-medieval sites, where considerable changes since their last use have taken place in the archaeological record over many years through normal site formation processes. This chapter will examine the initial stages in the formation of the archaeological record at a location by taking the example of two iron-working related sites, both at Rievaulx Abbey in North Yorkshire (Figure 10.1). The first site is that of an experimental iron smelting furnace, while the second was established on a temporary basis for a public demonstration of blacksmithing.

10.2 Experimental iron smelting furnace

The experiment was designed not only to replicate the manufacture of bloomery iron but also to demonstrate how such a furnace structure deteriorated over time after iron smelting ceased, i.e. to simulate the formation process of a medieval iron smelting site following its disuse and compare the current state of the process on a regular basis with the known, excavated iron smelting sites at Hagg End, Kyloe Cow Beck and Stingamires to the north of Rievaulx Abbey in Bilsdale. The comparison is made by means of geophysical survey using magnetic measurement techniques over the site of the experimental furnace, assessing the changes to the successive survey data which may have occurred and comparing these changes with the geophysical surveys which have been undertaken at the sites in Bilsdale noted above, some of which are indicated in Figure 10.1. Whilst this experiment is unique to Rievaulx Abbey and its environs, other researchers have carried out similar iron smelting experiments: for example, Crew (1991), Young (1999b), Hjärthner-Holdar *et al.* (1997), and Joosten *et al.* (1997).

10.2.1 Siting the furnace

The furnace was constructed in the grounds of the Abbey in an area of known low magnetic activity, described below; this was to ensure that any enhancement to the magnetic properties of the soil from the operation of the furnace would be observable through geophysical survey without being affected by background magnetic anomalies.

To determine the optimum position for the furnace, taking into account English Heritage requirements for siting the structure, including those for public safety, an initial magnetometer survey was carried out by Dr. R. Vernon over an area of the Abbey grounds to the west of the main ruins (at the time of writing, the survey has not been reported elsewhere). The instrument used was a Geoscan FM36 fluxgate gradiometer, covering twelve 20m x 20m grids at a resolution of 1m (1m intervals at 1m traverses), with the instrument sensitivity set to 0.1nT. The plot of the survey data is shown in Figure 10.2. The mean value of the raw data from these twelve grids is 1.2nT; the standard deviation is 21.8nT. The maximum positive and negative values recorded are 197nT and -194nT; these two readings are not related as they are about 13m apart, and consequently could have been generated by *inter alia* individual stray iron-based objects lying below the ground surface close to the line of trees indicated. Two 10m x 10m areas of the plot, A and B shown in Figure 10.2 and in more detail in Figure 10.3, were chosen as possible locations for the furnace. Of these, area A was observed to be the most magnetically "quiet" in comparison with Area B and the remainder of the survey. The mean value of the raw data from this area is 3.1nT; the standard deviation is 2.1nT. The maximum positive and negative values are 10nT and -3nT. For comparison purposes, the mean value of the raw data from area B is -16.5nT, the standard deviation 38.0nT and the maximum positive and negative values 197nT and -137nT. On the basis of the observed low magnetic data values, the decision was taken to build the furnace within area A. The location of the furnace and a general view are shown in Figures 10.4 and 10.5.

10.2.2 Pre-construction magnetic susceptibility surveys

All subsequent surveys around the furnace employed volumetric magnetic susceptibility measurements and were undertaken by the author using a Bartington MS2D field coil and the data recorded on a hand-held Psion data logger. It was considered that this particular geophysical survey method was entirely suitable in this location since any enhancement caused by the operation of the experimental furnace would be in the top layer of the flat grassy soil surface, and such a surface would allow for good field coil ground contact leading to reliable and consistent data recording.

An initial pre-furnace construction magnetic susceptibility survey was carried out over two 10m x 10m grids at a resolution of 0.5m (0.5m intervals at 0.5m traverses). These two grids, Grids 1 and 2, are shown in Figure 10.6 and correspond to the areas A and B (respectively) in Figure 10.3. The plot of the survey data is shown in Figure 10.7. The square-C shaped feature in the centre of the plot is as a result of dummy data having to be recorded due to the physical and magnetic interference caused by the scaffolding supporting an awning erected over the proposed position of the furnace to afford some protection from the weather. The mean value of the raw data from these two grids is 29 x 10^{-5} [SI], the standard deviation is 57 x 10^{-5} [SI], and the minimum and maximum values 1 x 10^{-5} [SI] and 459 x 10^{-5} [SI]. The mean value of the raw data from Grid 1 alone is 12 x 10^{-5} [SI] and the standard deviation is 10 x 10^{-5} [SI]. The minimum and maximum values are 1 x 10^{-5} [SI] and 157 x 10^{-5} [SI]. Compared to the mean value of 165 x 10^{-5} [SI] for the raw data from an area of the Kyloe Cow Beck iron smelting site, approximately 10km north of Rievaulx in Bilsdale, uncontaminated by the smelting activity, the mean values of the raw data from these two grids are very low and afford an excellent background against which any magnetic enhancement of the top soil could be contrasted.

A further pre-construction magnetic susceptibility survey was undertaken over a single 5m x 5m grid (Grid 3 in Figure 10.6) at the higher resolution of 0.25m (0.25m intervals and 0.25m traverses), within Grid 1 and surrounding the proposed position of the furnace. Figure 10.8 is the plot of this survey data; the two linear features running east-west on the left of the plot are the dummy data associated with the scaffolding noted above. The mean value of the raw data from this grid is 10×10^{-5} [SI] and the standard deviation is 3×10^{-5} [SI]. The minimum and maximum values are 1×10^{-5} [SI] and 24×10^{-5} [SI]. This single magnetic susceptibility survey accordingly became the benchmark against which subsequent surveys were to be compared, in order to measure the effect of iron smelting on the magnetic properties of the ground and the decay of the furnace after smelting has finished.

10.2.3 Furnace construction and operational details

Built on 8th June, 2002, the furnace was a cylindrical clay structure having willow withies as internal reinforcement and a rounded-square footprint. The original dimensions were:

Height	140cm	
Width	base:	93cm external, 40cm internal
	top:	95cm external, 42cm internal
Tapping arch	25cm tall x 22cm wide	

The internal dimensions were deliberately trimmed down to approximately 28cm in diameter to form a restriction or pinch point at a height of 83cm above the furnace base, to control the flow of the ore/fuel charge through the furnace as the smelting process progressed. Two opposing tuyeres (blowing holes) were built into the furnace during construction, situated at a height of 36cm above the base. The height of the furnace was reduced to 120cm before Smelt 5 on 3/5/03, and to 112cm before Smelt 7 on 28/6/03, in order to determine if this reduction in height had any effect on the smelting process. Six K-type thermocouples were located at various positions at the front and rear of the furnace.

The furnace operations and the associated magnetic susceptibility surveys were carried out over an 18 month period, as follows:

Initial magnetic susceptibility surveys	7 June, 2002
Smelt 1	21 June, 2002
Smelt 2	22 June, 2002
Magnetic susceptibility survey	23 June, 2002
Smelt 3	20 July, 2002
Smelt 4	21 July, 2002
Magnetic susceptibility survey	22 July, 2002
Smelt 5	3 May, 2003
Smelt 6	2 June, 2003
Smelt 7	28 June, 2003
Smelt 8	29 June, 2003
Magnetic susceptibility survey	5 July, 2003
Smelt 9	13 July, 2003

Smelt 10	10 September, 2003
Magnetic susceptibility survey	5 November, 2003

Furnace temperatures were measured throughout each of the smelting operations and consistently achieved above 800ºC in the furnace zone above the tuyeres, i.e. above the combustion zone, and up to 1100ºC in the same zone in the majority of the smelting operations. A temperature of 1356ºC was recorded in the combustion zone (below the tuyeres) in one 10 minute period during Smelt 10.

After the experimental smelting operations were completed the furnace structure was left to collapse and deteriorate naturally. Magnetic susceptibility surveys have been and will continue to be carried out to record the progress of the decay process; surveys undertaken so far:

5 November, 2003 (the initial decay process survey noted above)

19 April, 2004

2 June, 2006

10.2.4 Magnetic susceptibility survey plot analyses

The following are the analyses of all of the magnetic susceptibility surveys carried out over Grid 3 in Figure 10.6, pre- and post-construction of the furnace and during the early stages of the decay process. Each set of raw data has been interpolated four times – once each in the X and Y directions using the Sin(x)/x expansion method and again in both directions using the Linear expansion method. The furnace position is indicated on each survey plot and is scaled to the 93cm outside width of the structure.

10.2.4.1 Initial survey of 7th June 2002 (Fig. 10.8)

The surveyed area is magnetically "quiet"; the raw data mean, minimum and maximum values are noted in section 10.2.2 above.

10.2.4.2 Survey of 23rd June 2002 after the second furnace operation (Fig. 10.9)

The consequences of the initial two operations of the furnace can be seen. Some slag-like material was produced and raked out of the furnace, resulting in the small accumulation of relatively high value magnetic susceptibility readings in front of the tapping arch (feature A). The features B and C, and the group of relatively low value features D are almost certain to be pieces of the slag-like material being deposited away from the furnace by personnel walking around the furnace operating area. Feature E was caused by the accumulation of small amounts of iron ore being dropped in the ore preparation area.

10.2.4.3 Survey of 22nd July 2002 after the fourth furnace operation (Fig. 10.10)

The amount of slag-like material raked out from the furnace has increased, with the area directly in front of the tapping arch indicating an even greater accumulation of this material (feature A). On being raked out some of this material was also deposited to the north of the furnace (feature F). Features B, C, D and E correspond to those shown in Figure 10.9; feature B is now diminished (possibly trodden deeper or moved out of the survey area) but features C, D and E are all enhanced. Features G are areas randomly "seeded" with slag-like material as a result of personnel walking around the furnace operating area.

10.2.4.4 Survey of 5th July 2003 after the eighth furnace operation (Fig. 10.11)

Although almost a year has elapsed since the previous survey, which would have allowed the accumulation of slag-like material in 2002 to disperse partially, the amount of slag material produced in the furnace operations in May and June 2003 (Smelts 5 to 8 in the listing in section 10.2.3) was sufficiently high to show an increased accumulation in front of the tapping arch (feature A) and to the north of the furnace (feature F). All the remaining features, including B, show increased magnetic susceptibility values consistent with the amount of slag material produced and “walked” around. Note that although the scaffolding was still in position, it did not interfere with the data recording during this survey.

10.2.4.5 Survey of 5th November 2003 after the tenth (final) furnace operation (Fig. 10.12)

Features A and F (from Figures 10.10 and 10.11) and features G to the north and west of the furnace have merged, due to the large accumulation of slag material made from the last two furnace operations and deposited either deliberately from raking out the furnace or accidentally by “walking”. By the time that this survey took place the awning and its supporting scaffolding had been removed; other than the furnace there were no obstacles within the survey grid which made the data recording considerably easier.

10.2.4.6 Survey of 19th April 2004 after the start of the decay process (Fig. 10.13)

Although five (winter) months have elapsed since the previous survey, the shape of the relatively high valued anomaly adjacent to the furnace has not changed significantly, despite the potential for some of the magnetic material to leach into the sub-soil. The effect of part of the structure slumping over the area immediately surrounding the furnace is observable when comparing the survey plots in Figures 10.12 and 10.13, in conjunction with the photographs of the furnace before and after the start of the decay process (see paragraph 10.2.6). To the north of the furnace the magnetic susceptibility raw data values vary with distance from furnace base: *c*. 40 x 10^{-5} [SI] under the slumped clay at 25cm from the base, *c*. 1500 x 10^{-5} [SI] also under the clay at 50cm and *c*. 250 x 10^{-5} [SI] at 75cm near the edge of the slumped material. A similar but lower valued variation is seen to the south and south-west of the furnace within 50cm of the structure.

10.2.4.7 Survey of 2nd June 2006 after three winters following the start of the decay process (Fig. 10.14)

In the two year period since the previous survey the furnace structure has been subjected to the effects of a further two winters and freak weather conditions during June 2005. Despite these effects, the shape of the relatively high valued anomaly adjacent to the furnace has not altered substantially, although the levels of recorded magnetic susceptibility have reduced. To the north of the furnace, the raw data values at 25cm from the base were not able to be measured due to the greater amount of slumped clay, at 50cm the raw data averaged *c*. 200 x 10^{-5} [SI] and at 75cm, *c*.250 x 10^{-5} [SI]. Further out at 1.5m the average is c. 90 x 10^{-5} [SI] and at 2m, the current edge of the slumped material, is *c*. 77 x 10^{-5} [SI]. To the south and south-west of the furnace within 50cm of the structure the raw data values average *c*. 27 x 10^{-5} [SI]. All the features A to G noted in the previous surveys are still visible but at lower levels; for example, feature C has reduced from 153 to 47 x 10^{-5} [SI] when compared to the survey of 19th April 2004 (section 10.2.4.6). Similarly, the average value of the raw data recorded in the 1m square of feature F has reduced from 738 to 322 x 10^{-5} [SI] when compared to the same survey.

10.2.5 Magnetic susceptibility survey summary

The sections above detail the changes in magnetic susceptibility recorded in Grid 3 (Figure 10.6). In order to quantify the changes in magnetic susceptibility, the raw data from each of the surveys was analysed and the mean, standard deviation, minimum and maximum values calculated and tabulated (Figure 10.15(a)). There are significant changes in maxima from 24 x 10^{-5} [SI] to over 4000 x 10^{-5} [SI], particularly as a result of the furnace operations in 2003 when more slag material was produced than previously; the minima are virtually unchanged and can be considered as "control" values which indicate little or no extraneous magnetic material being brought into the survey area. The values for the initial magnetic susceptibility survey over Grids 1 and 2 are relatively high as they are influenced by the magnetic anomalies associated with the line of trees indicated in figure 10.2. The variation in mean values are plotted in Figure 10.15(b).

10.2.6 Post-operation monitoring: the furnace structure decay process

The next stage in the experiment was to observe the furnace structure deteriorating; this decay process is expected to take some time, possibly five to ten years, depending on the weather, seasonal changes and other factors such as human intervention. During this period, the furnace structure decay would be monitored by means of photography and magnetic susceptibility survey. It should be noted that Young's experimental furnace (1999b) is also being monitored; as part of the overall smelting experiment, the furnace has been abandoned since its last use in March 2004, left uncovered and its decay is being observed visually.

So far a series of photographs have been taken showing the changing state of the furnace, Figures 10.16 to 10.20, and are described as follows:

Taken at the time of the magnetic susceptibility survey in November 2003, the photograph of Figure 10.16 shows the furnace after its last operation and before the start of the decay process. A plastic tarpaulin had been placed over the furnace, held in place by logs at the side and on top, to protect the structure from the weather until such time when the decision was taken to expose the furnace and commence its decay. Despite the efforts of vandals who had attempted to set fire to the logs, the structure is seen to be intact. At this stage the furnace dimensions have not altered, i.e. base 93cm wide and height *c*. 110cm.

Figure 10.17 shows the furnace in April 2004, after one winter. The inner core of the structure is largely intact due to having been hard-baked and partially vitrified in the combustion zone at the level of the tuyeres and the top of the tapping arch. The outer part, being less baked and, therefore, more vulnerable to the effects of the weather, has peeled away from the inner core and slumped around the base of the structure. At this stage the slumped material has a diameter of approximately 1.5m, which would have covered part of the relatively high valued anomaly surrounding the furnace, seen in Figure 10.13. The height of the furnace has reduced to *c*. 90cm.

The state of the furnace in March 2005 after two winters is seen in Figure 10.18. It was considered unnecessary to record the state of decay during the summer and autumn months of 2004, as most of the decay would be caused by the effects of winter weather (rain and frost).

During June 2005 freak weather conditions resulted in serious flooding in the Ryedale area. Although there was severe damage to property including buildings in and around Rievaulx Abbey (fortunately not to the Abbey itself), the furnace was not destroyed. The photograph (Figure 10.19) taken in September 2005 shows the surviving structure, now reduced in height to *c*. 75cm. Some of the slumped material referred to above has probably been spread around the immediate furnace area or may have even been washed away, but the diameter remains around 1.5m.

Figure 10.20 is a photograph taken in May 2006 of the furnace structure after the effect of three winters. The furnace height is now *c*. 65cm and the diameter of the slumped material has now increased to around 2m.

Monitoring the physical state of the furnace will continue until the structure has virtually disappeared. It is anticipated that in several year's time, depending on the factors noted above, the furnace remains will consist of a shallow mound, estimated to have a diameter of not more than 3m, covering the immediate furnace area and the high valued magnetic anomaly. Magnetic susceptibility surveys of the furnace area should confirm whether this anomaly survives during the decay process.

10.2.7 Discussion

The sequence of magnetic susceptibility survey plots clearly shows the increasing magnetic enhancement of the area immediately surrounding the experimental furnace (Figures 10.8 to 10.12) and the reduction in enhancement after the start of the decay process (Figures 10.12 to 10.14). Most of the enhancement occurs within 2m of the furnace structure, an area which would have seen a considerable amount of magnetic material (predominantly slag) being deposited as personnel moved around the furnace during its operation. The increasing accumulation of slag material to the north (right hand side) of the furnace seen in Figures 10.10 to 10.12 is almost certainly due to the method of raking out. A right-handed person would rake the material out naturally to the right hand side and move (shovel) the rakings to the right (north) of the furnace; this was actually observed.

It was not possible to measure the magnetic susceptibility of the furnace internal ground surface, including the area within the vicinity of the tapping arch, during the period when the furnace was functional and later in the early years of its decay due to the physical construction of the Bartington MS2D instrument and the extant dimensions of the structure: the instrument would not fit into the furnace. Measurement might become possible as the furnace structure slumps during the decay process, but even then the instrument readings obtained are unlikely to represent the magnetic susceptibility of the internal surface as enhanced at the time of furnace operation, being modified by clay from the structure and other debris creating a layer over the original surface.

It is anticipated that the furnace decay will take a considerable time to progress to the point were the furnace has virtually disappeared; several years is estimated, during which time regular monitoring of the furnace's physical state and geophysical surveying will be required. The "end result" is predicted to be an almost imperceptible mound and a low valued magnetic anomaly probably coinciding with the area of slag deposits north of the original furnace structure, but this depends a great deal on how much human intervention (grounds maintenance and public access) is allowed over the furnace site.

The general decay process and in particular the effects of the floods in June 2005 on the experimental furnace have raised questions regarding the preservation and distribution of magnetic anomalies on similar sites lying at low level and close to natural water courses. The furnace decay so far has shown that the outer, more vulnerable part of the structure slumps around the inner core thus creating a cone-shaped feature, which as its height reduces and its diameter increases with time, will provide some measure of cover for the magnetic material which surrounded the furnace during the later stages of its operation and which is now underneath the “cone”. This magnetic material is thus protected by an insulating layer or blanket of clay so preserving it to some extent from the weather and non-deliberate human intervention, whilst the magnetic material which is still close to the furnace but not under the slumped clay will gradually disperse.

To gauge the effect of the furnace construction material’s susceptibility on the magnetic susceptibility surveys during the decay process, samples totalling *c*. 150g were obtained from the bulk clay material and subjected to laboratory measurements to determine the mass specific susceptibility (χ) and density (ρ); the results were $\chi = 13 \times 10^{-8}$ m^3 kg^{-1} and $\rho = 1.6 \times 10^3$ kg m^{-3}. For direct comparison with the survey data recorded by the Bartington MS2D instrument, the volume specific susceptibility (κ) was calculated to be 21×10^{-5} [SI], from $\kappa = \chi.\rho$. (Note that these figures are compatible with those quoted by Hunt *et al.* (1995) in their Table 1, showing data for “clay”: $\chi = 10$ to 15×10^{-8} m^3 kg^{-1}, $\rho = 1.7 \times 10^3$ kg m^{-3} and $\kappa = 17$ to 25×10^{-5} [SI].) Depending on the thickness of the clay blanket, with its comparatively low magnetic susceptibility of 21×10^{-5} [SI], the magnetic anomalies previously recorded as having high values of susceptibility will now appear to have lower values. Conversely, the area surrounding the furnace, i.e. within the 5m square grid but not directly affected by the furnace operation, will appear to have higher susceptibility as a result of the furnace structure slumping and spreading outwards. The extent to which this slumping/spreading has influenced the magnetic characteristics of the area can be assessed by comparing the raw data of two specific areas, namely the bottom left and bottom right 1m squares of the survey grid, from the initial survey of 7th June 2002 with that of the 2nd June 2006 survey. These two squares were chosen as they had very little "traffic" over them and, therefore, would not have been significantly contaminated with magnetic material from the furnace operations. For the bottom right hand square, the raw data mean values are 9 x 10^{-5} [SI] (7th June 2002) and 22 x 10^{-5} [SI] (2nd June 2006). The corresponding values for the bottom left hand square are 11 x 10^{-5} [SI] and 21 x 10^{-5} [SI]. It is clear that some enhancement has occurred and that the most probable cause is the spreading of the clay structure as the furnace decay progresses.

It is also highly likely that alluvial cleansing from occasional river flooding will cause magnetic material, such as slag and baked clay from furnace structures, whether protected as described above or not, to be spread out away from the site of the furnace generally in a downstream direction; there will be a corresponding "thinning out" of the data recorded in a magnetic survey by both the increased spread of magnetic anomalies and the dilution of anomaly data values when compared to the data recorded in any magnetic surveys which may have been carried out before flooding occurred.

A comparison can be made with the iron smelting site at Hagg End, situated 15 to 20m west of and 2m above the present course of the R. Seph in Bilsdale north of Rievaulx. It is possible that this site has in the past suffered flooding, as assessed by the spread of magnetic material recorded in magnetic susceptibility surveys carried out in July 2003 (see Chapter 3). When surveyed, an area south of the Hagg End furnace recorded a magnetic susceptibility range of 40 to 1200 x 10^{-5} [SI] (mean *c.* 350 x 10^{-5} [SI]) which could be the remains of the slag heap spread over a broad area by the effects of flooding (Figure 10.21). Higher values of magnetic susceptibility data are to be expected at Hagg End as the furnace was certainly operated over a longer period compared to the

Rievaulx experimental furnace (the precise timescale is unknown but as the furnace was found to have had at least three repairs to its lining, it is likely to have been several years). The spread of data is probably caused by the effects of river flooding and to a lesser extent by the run-off from the moorland above the site. It would be speculative to suggest what anomalies a pre-flood survey would reveal, but the fact that the data were recorded over a wide area downstream of the furnace remains is a good indication of what could potentially happen to a low lying site similar to Hagg End.

10.3 Blacksmithing demonstration

During the open days held at Rievaulx Abbey on 21st July 2002 and 29th June 2003, a demonstration of blacksmithing was given to the public, affording them the chance to observe the basics of the craft. The author took advantage of these demonstrations to evaluate the effect of blacksmithing on the magnetic properties of the area where the demonstration took place and to make comparisons if possible with known archaeological blacksmithing sites. The measurement of any enhancement would be by magnetic susceptibility survey alone for the same reasons as given for the experimental iron smelting furnace surveys (see section 10.2.2). In contrast to the siting of the experimental furnace, the blacksmithing demonstration was set up in an area chosen by English Heritage as the best place for public viewing consistent with safety.

10.3.1 The location of the blacksmithing demonstration

The blacksmithing demonstration was set up on both open days in the area of the Abbey grounds believed to be where a fulling mill operated, which was approximately 20m south-east of the experimental iron smelting furnace. Figure 10.22 shows the blacksmithing area survey grids and their relationship to the experimental furnace superimposed on the magnetometer survey plot (compare with Figure 10.2). Although no pre-demonstration surveys were specifically undertaken over the blacksmithing area, the data from the magnetometer survey used to determine the optimum location of the experimental furnace was analysed over the four 5m x 5m grids shown in Figure 10.22, in more detail in Figure 10.23 and in Figure 10.24. The mean value of the raw data, which had been recorded at a resolution of 1m (1m intervals at 1m traverses), from these four grids is 2.6nT; the standard deviation is 15.3nT. The maximum positive and negative values recorded are 91nT and -110nT; these two readings are single points next to each other and may be caused by *inter alia* a stray iron-based object. Specifically, the raw data values within the demonstration area (Grid 2 in Figure 10.24) are: mean 2.2nT, standard deviation 29nT, maximum positive 91nT and maximum negative -100nT. The raw data from these grids indicate that the area could be regarded as magnetically "quiet" and as a result any magnetic enhancement of the top soil caused by the demonstration would be easily recorded above the low background level.

10.3.2 Observations

As stated above, the blacksmithing demonstrations took place on two separate occasions. The approximate positions of the blacksmithing equipment are shown in Figure 10.25; an extra anvil (A2) was used during the June 2003 demonstration (there were two blacksmiths). A series of photographs was taken (in June 2003) which indicated the physical relationship of the anvils, hearth and vice in the demonstration area, and some of the blacksmithing debris scattered around the bases of anvil (A1) and the vice (Figures 10.26 to 10.28). This debris was seen to have flaked off the surface of the iron being worked, either by hammering on the anvil or twisting in the vice, and on the assumption that it was hammerscale was expected to have a relatively high magnetic susceptibility value which would be recorded in the subsequent surveys. The anvil(s), hearth and vice were spread out within the demonstration area (Figure 10.26) which meant that there was considerable distance between the three working zones, much more than in a genuine blacksmith's shop. It was anticipated that as the blacksmiths moved between the work zones, "pathways" would be created which might be detected by the magnetic geophysical surveys as a consequence of deposition of magnetic particles from the blacksmiths' work wear.

The waist-high hearth (Figure 10.26) was constructed and operated in such a way that little or no heat from it was transmitted into the ground. No magnetic enhancement was expected from this source but was considered likely from magnetic debris either falling from the heated iron bars as they were removed from the hearth or from being "walked" into the vicinity of the hearth from the other working zones around the anvil(s) or the vice. Hammerscale was observed flying off in all directions as the iron bars were being worked at the anvil(s) (Figure 10.27). The blacksmith's apron as well as giving protection to the blacksmith would also cause the hammerscale to fall at his feet, leading to a concentrated accumulation of magnetic debris in front of the anvil compared to lower accumulated amounts in other directions. This would result in a particular magnetic response recorded by a magnetic geophysical survey. Figure 10.28 shows the accumulation of hammerscale around the bases of the vice and one of the anvils (the accumulation around both of the anvils was similar). Although the demonstrations were only one-day events and, therefore, the quantity of magnetic debris produced would be limited, it was anticipated that for each event the subsequent geophysical survey would record the various resulting magnetic patterns. In addition, the magnetic enhancement from the first demonstration in July 2002 was not expected to be observed in June 2003, due to the limited accumulation of magnetic material being spread around and outside the demonstration area by the effects of weather, public access and grounds maintenance during the intervening months.

10.3.3 Magnetic susceptibility surveys

The surveys which followed each of the blacksmithing demonstrations employed volumetric magnetic susceptibility measurements and were undertaken by the author using a Bartington MS2D field coil and the data recorded on a hand-held Psion data logger. This geophysical survey method was used for the same reasons as the magnetic susceptibility surveys over the experimental iron smelting furnace: any enhancement would be in the top layer of the flat grassy soil surface, which would allow for good field coil ground contact leading to reliable and consistent data recording. On both occasions, the magnetic susceptibility survey was undertaken over the four 5m x 5m grids shown in Figure 10.24, at a resolution of 0.25m (0.25m intervals and 0.25m traverses).

The plot of the July 2002 survey is shown in Figure 10.29(a). The mean value of the raw data from this survey is 25 x 10^{-5} [SI] and the standard deviation is 50 x 10^{-5} [SI]. The minimum and maximum values are <1 x 10^{-5} [SI] and 1012 x 10^{-5} [SI]. The high valued maximum was an anomaly adjacent to the anvil and was probably generated either by an accumulation of hammerscale or a single piece of iron-based material. Whatever the cause of this anomaly, it was as a result of the blacksmithing activity since no high valued anomaly had been recorded in this location by the magnetometer survey (see section 10.3.1). Since no blacksmithing activity took place over nor public access was allowed to Grid 4 (Figure 10.24), the raw data from this grid were used as a benchmark for comparing other magnetic susceptibility survey data. Ignoring the relatively high valued rectangular anomaly in the top left (a medieval tiled hearth), the raw data values from Grid 4 are: mean 13 x 10^{-5} [SI], standard deviation 4 x 10^{-5} [SI], minimum 8 x 10^{-5} [SI] and maximum 33 x 10^{-5} [SI]; these values are similar to those from the experimental iron smelting furnace pre-construction magnetic susceptibility survey over Grid 3 (see section 10.2.2).

The plot of the June 2003 survey is shown in Figure 10.29(b). The mean value of the raw data from this survey is 26 x 10^{-5} [SI] and the standard deviation is 38 x 10^{-5} [SI]. The minimum and maximum values are <1 x 10^{-5} [SI] and 446 x 10^{-5} [SI]. The high valued maximum was an anomaly adjacent to anvil A2 and was probably generated in a similar manner to the maximum value noted above in the July 2002 survey; the highest value in the vicinity of anvil A1 was 235 x 10^{-5} [SI]. The raw data values from Grid 4 are: mean 14 x 10^{-5} [SI], standard deviation 6 x 10^{-5} [SI], minimum 8 x 10^{-5} [SI] and maximum 61 x 10^{-5} [SI]; these values are very similar to those from the July 2002 survey and suggest that there had been very little magnetic contamination of Grid 4 over the previous year, and by inference over the blacksmithing demonstration area.

10.3.4 Magnetic susceptibility survey plot analyses

The following sections analyse the magnetic susceptibility surveys over the grids in Figure 10.24, carried out separately in July 2002 and June 2003. Each set of raw data has been interpolated four times – once each in the X and Y directions using the Sin(x)/x expansion method and again in both directions using the Linear expansion method. Reference should be made to Figure 10.24 for the location of the individual grids within the surveyed area.

10.3.4.1 Survey of 22nd July 2002 (Figure 10.30(a))

Grid 4 (the raw data benchmark grid) is magnetically “quiet”, ignoring the response from the medieval hearth. The underlying response from Grid 2 (the demonstration area) can be assumed to be similar, as the same amount of “traffic”, i.e. public access and grounds maintenance, has taken place over this area. Accordingly, the enhancement to the magnetic properties of the top soil should be, and are, easily detected. Distinct areas of enhancement can be observed in Grid 2, corresponding to the positions of the anvil (A), hearth (H) and vice (V). The enhancement around A is particularly clear, and to a lesser extent around V. There is, as expected, no enhancement due to the operation of the hearth itself. The pathways A-V and A-H are just discernible; the short pathway eastwards from H is towards a chair (seen in Figure 10.26).

10.3.4.2 Survey of 30th June 2003 (Figure 10.30(b))

Grid 4 remains magnetically "quiet"; no additional enhancement to the top soil is seen in this grid or in Grid 2. Similar to the previous survey, distinct areas of enhancement in Grid 2 are present, corresponding to the positions of the anvils (A1 and A2), hearth (H) and vice (V). The enhancement around both anvils is clear, especially around A1, whilst the anomalies associated with H are probably due to magnetic debris being either deposited from the iron bars heated in the hearth as they were transported to the anvils or "walked" into the vicinity. The A1-A2-H pathways are also just discernible, but there is no detectable pathway between the vice and any of the other work areas. Similar to the previous survey, there is a short pathway from H eastwards.

10.3.5 Discussion

Although these two short demonstrations gave a good impression of blacksmithing activities and the skills involved, they were essentially artificial due to the constraints imposed by time, location and concerns over public safety; the work areas of hearth, anvil and vice were spread out further than would normally occur.

The Rievaulx blacksmithing demonstrations are good examples to use when considering the notion of blacksmithing as either an internal or external industrial activity, i.e. within a fixed purpose-built location or as a transient occupation within a temporary, possibly transportable structure (G. McDonnell, pers. comm.). In practice, a "fixed" smithy operating over a considerably longer timescale than the demonstrations would have the work areas much closer together, possibly within two or three paces of each other so as to minimise heat loss in the iron workpiece. As a consequence, there would be a greater concentration of hammerscale and other magnetic debris within the smithy, and the accumulation over time would result in geophysical magnetic surveys recording high valued anomalies in a relatively small area.

Two examples of long-term, internal blacksmithing activity are presented for comparison: Burton Dassett (Warwickshire) and Westhawk Farm (Kent). It would be expected that the accumulation of debris from either of these two smithing sites would be much greater than that from the Rievaulx demonstrations. During the excavation of the deserted medieval market town of Burton Dassett, the site of an iron smithy was identified by the presence of large quantities of smithing debris, including hammerscale (McDonnell 1992); the amount of slag material suggested that the smithy had been in use for many years. Mills and McDonnell (1992) concluded that the building was a smithy not just from the amount of hammerscale but also the range and distribution of the susceptibility of the recovered magnetic debris. The magnetic susceptibility measurements which were carried out showed that there was a varying concentration of hammerscale specifically within the smithy itself, ranging from 47 to 4018 x 10^{-8} SI/kg (*sic*) (Mills and McDonnell 1992). Figure 10.31 is a plan of the smithy with a corresponding magnetic susceptibility contour map. The high values of magnetic susceptibility occur primarily along the north wall of the building to the west of the central structure (contexts 2067 and 2068 adjoining 2174, in Figure 10.31), in shallow depressions and close to the central structure, whilst low values occur at each end of the building, particularly the east end, and inside the central structure. Mills and McDonnell (1992) state that it is to be expected that smithing debris accumulates along wall lines and collects in depressions, unfortunately without explanation. The low magnetic susceptibility values within the central structure suggests the location of a waist-high hearth, whilst the other high values indicate the probable work areas surrounding the anvil and other smithing equipment. There is possibly only one pathway suggested by the magnetic susceptibility contours, running westwards of the central structure/hearth. The low values noted at the east end of the building and to a lesser extent at the opposite end strongly suggest that the smithing activity took place centrally, within an area approximately 5m by 3m, equating to movement between the anvil, hearth, etc. of two to three paces. Over a long period of smithy use, the working area surface would be composed of accumulated smithing debris (mainly hammerscale) which would be likely to blur any pathways of activity within the working area, making them difficult to define through geophysical survey. Outside the working area, where the accumulation of hammerscale is smaller by comparison (as demonstrated by the contour map in Figure 10.31), any pathways would be much easier to determine.

Paynter (2007) has reported on the excavations of two successive iron workshops at the Romano-British settlement at Westhawk Farm near Ashford, Kent; these workshops were discovered through the wider geophysical survey and excavation of the settlement during 1996-97 (Philp 1998) and the magnetometry (fluxgate gradiometer) surveys undertaken at 0.25m and 0.5m resolution over the site are discussed in detail in Vernon (2004: 86-87). In the better preserved of the two workshops, as well as a number of smelting furnaces, a smithing area was discovered which had a thick occupation surface of hammerscale. The concentration of hammerscale varied across the smithing area but the main and highest concentration was adjacent to a large vessel, suggesting that an anvil was situated nearby (Figure 10.32). Although Paynter suggests that there were possibly two anvil sites within the smithy, the one indicated in the figure is the more likely. An isolated area of accumulated hammerscale approximately 1m from the anvil could be the location of another piece of smithing equipment, but could also be a "pathway" described by Paynter as "probably a result of individuals treading the hammerscale across the floor as they exit through the eastern corner" of the workshop. The feature H in Figure 10.32, described as "maybe all that remains of a ground-level smithing hearth", has low concentrations of magnetic material surrounding it, which is consistent with the comparative waist-height feature at Rievaulx. The distance between the work areas of hearth and anvil is around 1m. The interiors of two smithies, seen in Figure 10.33, show the typical layout of blacksmithing equipment. Both smithies were originally built in the 18th Century, and although restored and no longer in commercial use, they do illustrate a layout and a close-positioning of equipment which may be seen in any blacksmith's workshop and which appears to have changed little over many centuries.

The Rievaulx demonstrations can also be employed to discuss external or transient blacksmithing and its potential for magnetic enhancement of the working surface. The concept of the transient or itinerant smith as described by Budd and Taylor (1995), originally in relation to the transition from the Bronze to the Iron Age, may also be applied to the medieval and post-medieval periods. Hinton (1998) observes that several studies have attempted to establish whether early Anglo-Saxon artisans were itinerant or sedentary, without satisfactory results. Similarly, the excavations of the Anglo-Saxon settlement at Mucking (Hamerow 1993) indicate the ambivalence of much of the evidence, which possibly represents an occasional visit by an itinerant smith. Evidence from excavated metalworking activities in Canterbury (Blockley *et al*. 1995) suggests that there may have been no permanent workshops, with production only taking place on an occasional or seasonal basis, possibly when royalty visited and assemblies were held.

The itinerant blacksmith did not have a fixed location to work in, often outside the confines of a village, but moved from settlement to settlement, or possibly from one town fair to another, remaining separate from the local people, and staying long enough for the work to be done before moving on. The time period between the blacksmith's visits might be sufficiently long enough for the hammerscale and other smithing debris from one visit to have dispersed before the next (compare the survey data from the second Rievaulx demonstration with the first, in section 10.3.3). Under these circumstances, and in contrast with the long-term fixed location activity described earlier, the quantity of smithing debris would be much smaller and unlikely to accumulate in any great quantities. Consequently, the magnetic enhancement to the blacksmithing area would be limited and not easily detectable using magnetometer or magnetic susceptibility survey methods.

10.4 Conclusions

The analyses of the magnetic susceptibility survey plots in sections 10.2.4 and 10.3.4 are not strictly true interpretations of the data as would be used for surveys over sites where activities producing magnetic anomalies were not known or understood; the cause of the magnetic anomalies on both Rievaulx sites (the experimental iron smelting furnace and the blacksmithing area) is already known, having been observed in action during the various operations of the furnace and the blacksmithing demonstrations.

Being aware of how the “patterns” of the magnetic anomalies are derived from these two sites will go some way towards the better interpretation of activities on other similar archaeological sites.

The experimental furnace has been shown to be a useful exercise in understanding the process of iron smelting. With particular reference to this research, operation of the furnace has demonstrated a possible mechanism for enhancement of the magnetic properties of the ground on which the furnace was built. Although the furnace decay is expected to last several years, the decay so far has resulted in sufficient information to go some way in explaining how and why the magnetic remains of iron smelting furnaces, either recorded through geophysical survey or soil sample analysis, are as they are. Further investigations into iron smelting and its effects on magnetic properties are required, subject to appropriate resources; another experimental furnace should be considered but this time built into banking similar to that which has been commonly found on iron smelting sites, such as Kyloe Cow Beck and Hagg End (both in Bilsdale, North Yorkshire) and Ashwicken, Norfolk (Tylecote and Owles 1960).

The blacksmithing demonstrations, even though they were unique and artificial in their location and equipment layout, illustrated how the magnetic properties of the working surfaces in a blacksmithy can be generated. In continual use these working surfaces become saturated with hammerscale and other magnetic debris, such that the concentration of magnetic material builds up around the blacksmithing equipment: high concentrations around the anvil, lower intensities adjacent to the hearth and even lower amounts in inaccessible or non-work areas such as storage places or under bellows. These different concentrations when plotted as magnetic contours can be regarded as characteristic of smithies in general and consequently will invaluable in the interpretation of geophysical surveys over such sites. However, whilst this is true for blacksmithies in fixed locations, transient or itinerant smithies are ephemeral in nature, leaving little or no evidence of their existence in the archaeological record.

This study has identified the need for a higher resolution approach to site investigation and recommendations for consideration are made in Chapter 12, section 12.2.7.